MIT'S MAGAZINE OF INNOVATION

TECHNOLOGY REVIEW

MAY • JUNE 2000

THE FUTURE OF COMPUTING

BEYOND SILICON

A special issue devoted to exotic approaches based on DNA, individual molecules, cells and quantum properties

PLUS

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Steven Pinker on Human Nature

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{How technology lets you experience

Agility, as defined by Corv

By Cheryl Pilcher, Corv

Taking one of the world's premier sports cars to the next level of performance is not an easy task, or one we take lightly. Corvette® owners are

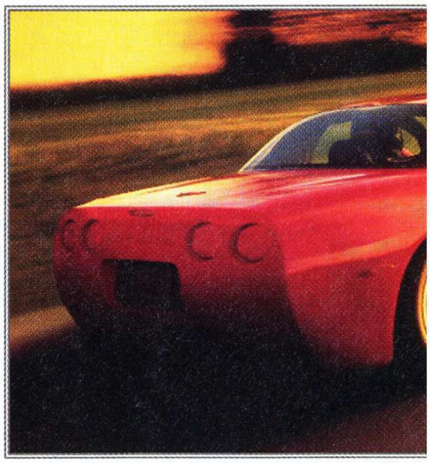
{ Corvette coupe features include an easily removable one-piece top with magnesium frame. }

enthusiasts, and when we consider enhancing their driving experience, we do so with the knowledge that we must do *exactly* that. Esoteric engineering exercises that result in little or no benefit to the driver have no place in the Corvette mission.

What Is Active Handling? Corvette Active Handling is the logical next step in the evolution of enhanced chassis control systems like ABS brakes and Traction Control. The available Active Handling System activates when there is a significant difference between how the driver *intends* for the car to corner and how the car is *actually* cornering. Working with the ABS, it automatically applies any of the four brakes to help actively control the situation.

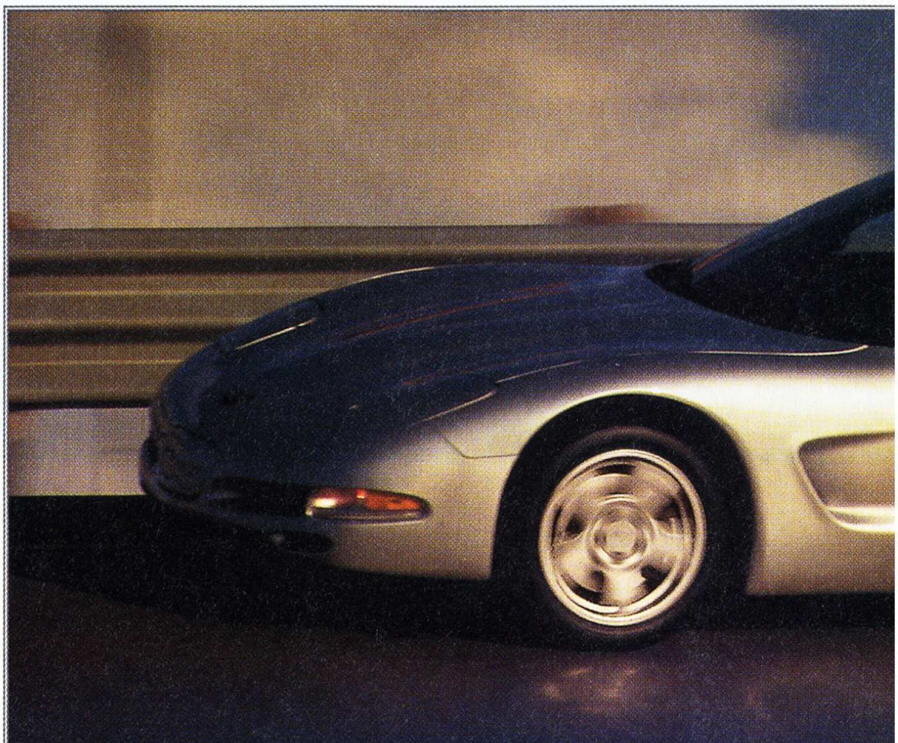
The Tough Part, Really, Is the Human Part. The thing we've learned about Corvette drivers is that it's not only the car's performance that they love, but it's being *in control* too. Active Handling had to be developed to enhance the driver's control without being intrusive. Before we could create the algorithms for the software, we had to drive thousands and thousands of miles, *anticipating* virtually every driving situation imaginable, not only on dry roads, but on wet and snowy roads, too. This is what we mean by the human part. Computers are great. But you have to collect accurate data and set up the computers properly to deliver the kind of driving experience that a Corvette driver demands.

Agility and Subtlety for the Real World. The available Corvette Active Handling System offers amazing agility for the kinds of situations you encounter in real-world driving. Imagine a sudden lane change on a wet road surface to avoid an unexpected hazard — like a huge pothole. Let's say you turn the



{ Performance for performance sake, the hardtop

wheel sharply to the left to avoid it. This input, combined with the low-traction surface, could exceed the limits of traction available to the front wheels, causing "understeer," allowing the car to "plow" straight ahead. In this situation, Corvette



Corvette to its fullest capability.}

ette with Active Handling.

ette Engineering Group

is the ultimate Corvette for sports car purists. }

Active Handling will work to help correct the car's understeer condition by automatically applying the left rear brake, coaxing the car to the left. Of course, an aftereffect of this maneuver could be that the tail of the car may actually start to swing out the other way in a classic "oversteer" condition. The subtlety of Corvette with Active Handling is that it responds to this natural overreaction and brings the rear of the car back in line. Yet its operation is so sophisticated, the chances are good that you will never sense the system's activation.

A Note of Caution: The overall effectiveness of the Corvette Active Handling System is directly related to available tire traction and the aggressiveness of a given maneuver. Active Handling is designed to use existing traction to assist the driver — *but it cannot overcome the laws of physics. Please drive responsibly.*

Competitive Driving Mode for the Track. The Corvette Active Handling System is the first of its type in the world to offer dual-mode operation. You can engage a *competitive driving* mode for autocross, gymkhana or other on-track activities. In this mode, Active Handling remains fully functional—

{ The C5 was designed from day one to be a world-class sports car that's also a convertible. }

while the traction control is disabled, allowing for some wheelspin and oversteer, so more experienced drivers can enjoy the dynamic capabilities of Corvette on the track.

This Is a Corvette to Love. You have to drive the 2000 Corvette with available Active Handling to appreciate how great it really is. We set out to design the ultimate Vette for enthusiasts and I think we knocked it out of the park. We love driving it. And we think you'll love it too.

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CORVETTE

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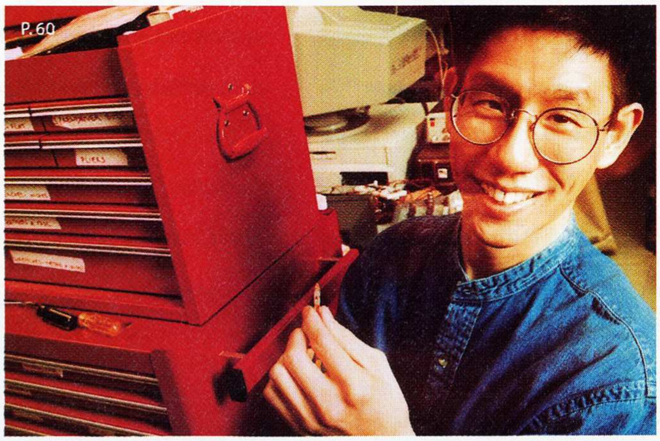

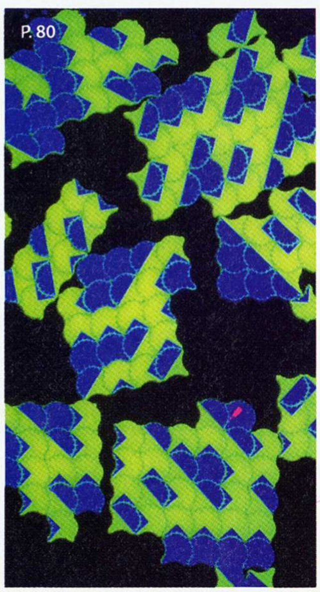

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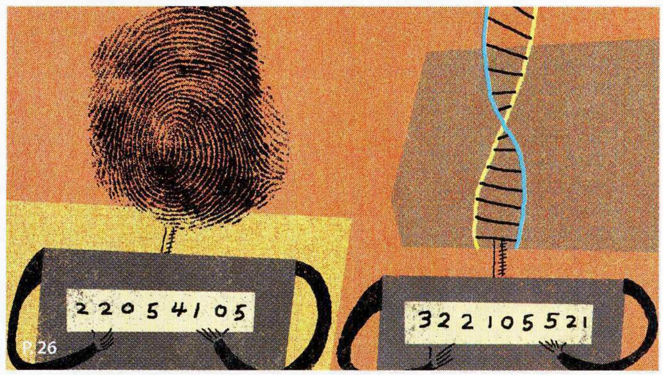

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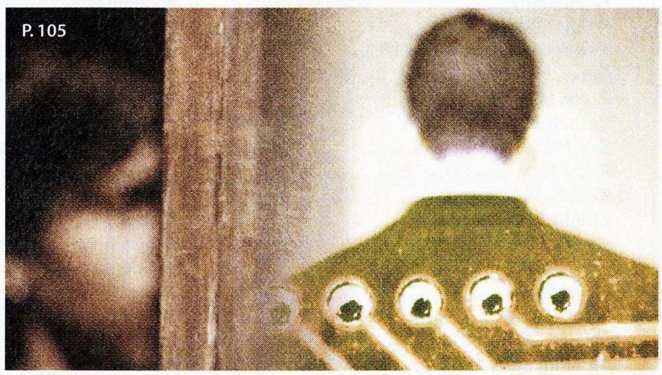

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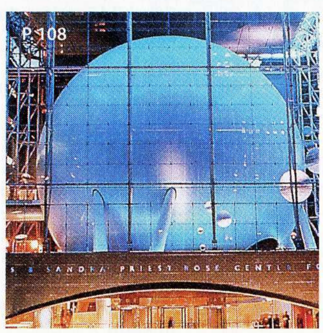

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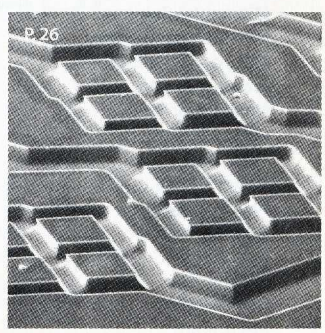

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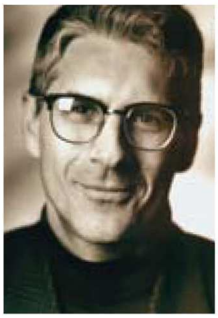
Sands of Time

YOU HOLD IN YOUR HANDS THE FIRST SPECIAL ISSUE OF *TECHNOLOGY REVIEW* FOR 2000. It's on a subject we think will increase in importance not just through this year but for the rest of the decade and perhaps for the rest of the new century. That subject: What happens after current silicon-based computing technologies begin to reach the limits of their rapid increase in speed?

For the last four decades, computers have presented a remarkable picture. While dramatically increasing in speed and computing power, they've also dropped precipitously in price. Underlying this pattern is a rule of thumb known as "Moore's Law," named for Intel co-founder Gordon Moore, who formulated it in the 1960s. Moore hypothesized that engineers would be able to squeeze more circuit elements into integrated circuits at a pace that represented a doubling every year or so.

The exponential growth in computing that Moore described underlies the growth of the Internet and the accompanying economic boom we're now experiencing. Which brings up the unsettling question of what happens when Moore's Law runs out of gas.



After all, it's not a law of nature. It's just a rule of thumb describing what's happened in one industry—computer manufacturing—over a couple of decades. Nothing says it's eternal. Indeed, there have been plenty of cries of alarm before about the end of Moore's Law, but, as Charles Mann points out in his introductory article ("The End of Moore's Law?" p. 42), this time there is ample reason to take the alarms seriously.

If silicon-based computing technology reaches its limits in the next decade, what is waiting in the labs to take its place? That's the question this special issue takes on. In four articles on new approaches to computing—Molecular Computing (p. 52), Quantum Computing (p. 60), Biological Computing (p. 70), and DNA Computing (p. 80)—the issue outlines how the process of computation can be divorced from silicon and embodied in new mediums.

None of these approaches is ready to serve as an all-purpose replacement for silicon. In fact, one or more may never be more than specialized methods applied in particular niches, such as high-level cryptography. Which raises the question of why major corporations would invest money, time and energy in researching such high-risk propositions. Robert Buderi gives some surprising answers to that question (p. 88) and follows it up with an interview with Carly Fiorina, the new CEO of Hewlett-Packard (p. 94)—a company that is taking molecular computing very seriously.

Although all of these new approaches are high-risk research ventures, one of them, or one of their technological descendants, might one day turn out to be as revolutionary as integrated circuits incised on silicon chips. We won't know which one for some time, since it takes a good long while for a profound new technology to work its way out of the laboratory and transform the economy. But if you want to stay ahead of the curve, you can't wait until the results of that new technology are evident to all. You have to start looking much earlier, when that revolutionary new technology is being born in cutting-edge laboratories, academic and corporate. For those who want early warning of the next computing technology with the potential to be as revolutionary as silicon, the time to pay attention is now. And this issue is the place to start.

—John Benditt

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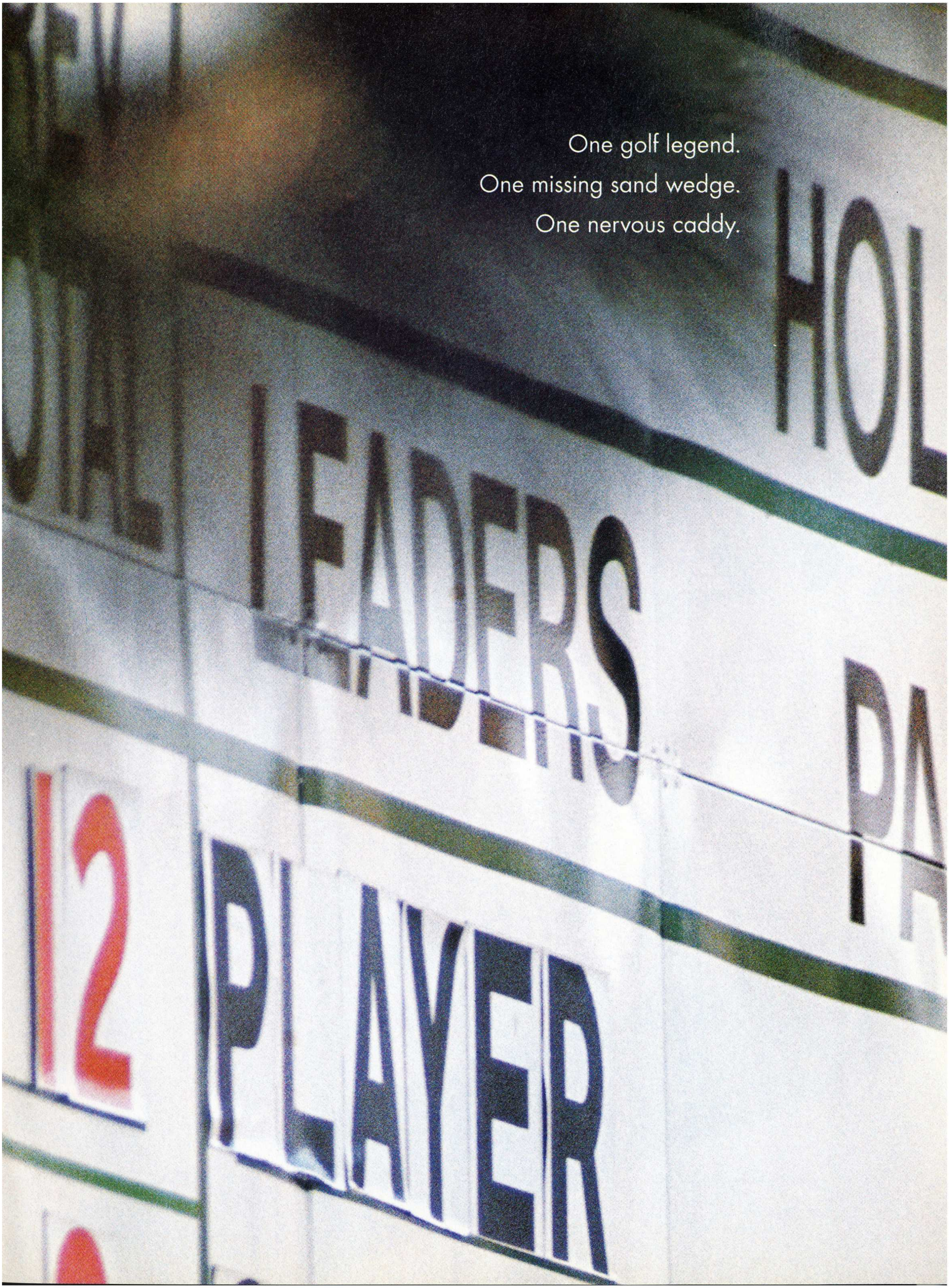
One golf legend.
One missing sand wedge.
One nervous caddy.
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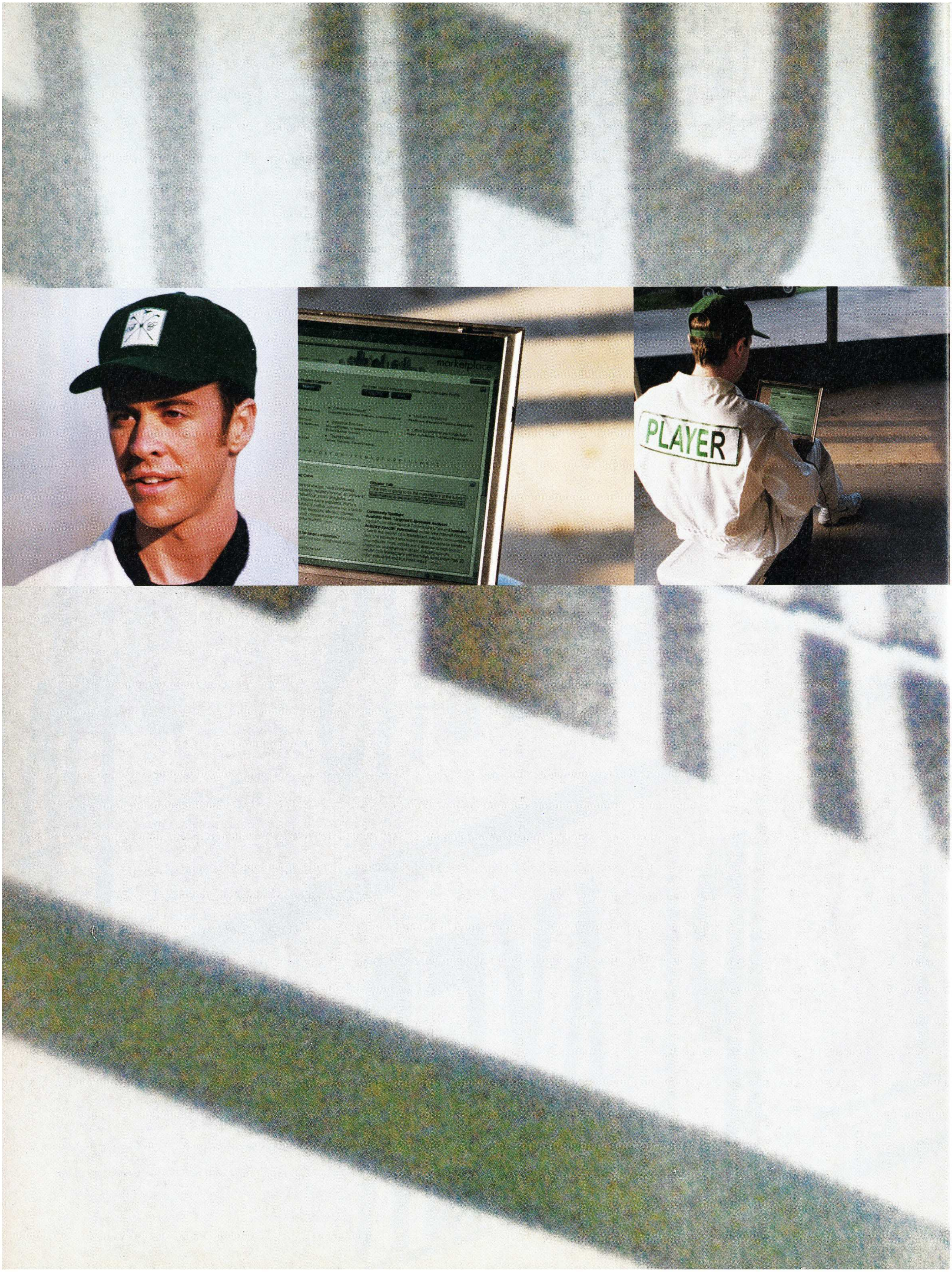
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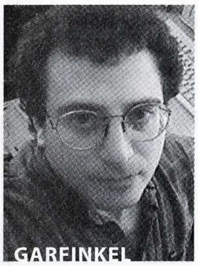
What lies "Beyond Silicon?" Some of the alternatives are, well, pretty strange. On p. 60, freelancer **M. Mitchell Waldrop** takes readers on a trip to the mind-warping world of quantum computers. Waldrop, who holds a PhD in particle physics, says this mixing of binary bits and sub-atomic particles reminds him of the scientific explosion in complex systems, which he documented in his 1992 book *Complexity.* "What I find so compelling is how these cross-disciplinary connections can lead to new insights," says Waldrop. In this case, he says physicists are beginning to suspect that Nature's laws may be "essentially computational in nature." | If quantum computers work, they could prove fast enough to break any cryptographic code, leaving no communication secure from prying eyes. That's a topic close to the heart of *TR* contributing writer **Simson L. Garfinkel**, the author of *Database Nation: The Death of Privacy in the 21st Century,* (O'Reilly & Associates, 2000). Garfinkel is an MIT grad whose inside track on the famed Laboratory for Computer Science (see his history of the lab in *TR*'s May/June 1999 issue) alerted him to some MIT computer scientists who are making the leap from electronics to bacteria. See "Biological Computing," on p. 70. | Although research into new computing paradigms is a high-risk venture, companies like IBM and Lucent don't hesitate to toss money at it. Why? *TR* contributing writer **Robert Buderi** explains "The Corporate Logic" on p. 88. Buderi's examination of corporate innovation, *Engines of Tomorrow: How the World's Best Companies Are Using Their Research Labs to Win the Future,* has just been published by Simon & Schuster. | As a journalist who owns four computers, **Charles C. Mann** takes a personal interest in the so-called "productivity paradox" that has left economists hard put to prove that computing advances have improved productivity levels—until recently. In "The End of Moore's Law?" Mann reports that productivity levels are edging up "but we still don't know why it has taken so long, or why the impact isn't greater." | Photo-illustrator **Jana Leōn's** images for Mann's piece were inspired by a firsthand experience with Moore's dictum. During a recent trip to the computer store she says "the sales people insisted I wait a month for the 'newest,' most powerful computer. Then another month for the newest printer, etc..." Leōn finally settled on a Macintosh G4, but she still relies entirely on manual darkroom tricks like layering negatives to create her collage-like pictures. "I like the irony of illustrating hi-tech this way," says Leōn. | Describing the far-out future of computing in words isn't easy. That's why in this issue, *TR* readers will find several "infographics" created by freelance art designer **Betsy Hayes** of Peep! Illustration & Design in Dover, Mass. "I try to make information look simple and inviting," says Hayes, who excels at the challenge of using graphics to explain *TR*'s complex subjects. | No matter what shape the computer of the future takes, humans will have to operate it. And that, argues **Steven Pinker** in this issue's Viewpoint, "Life in the Fourth Millennium," is why tomorrow's technology may not be as exotic as the futurologists would have us think. A professor of psychology in MIT's Department of Brain and Cognitive Sciences, Pinker is the author of *How the Mind Works* (Norton, 1997), a popular take on human nature. TR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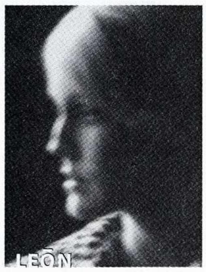
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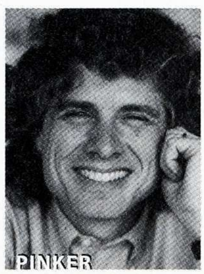
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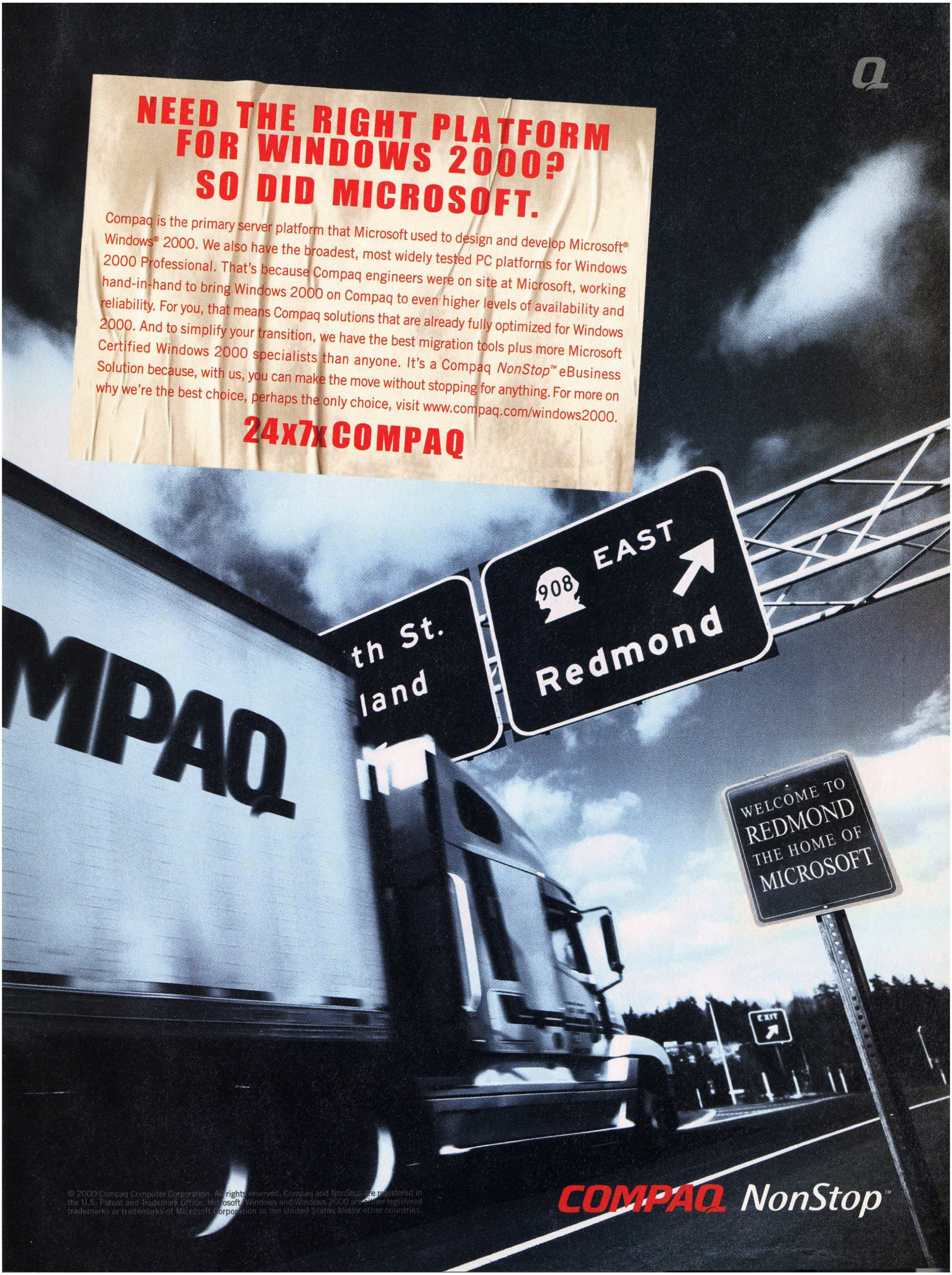
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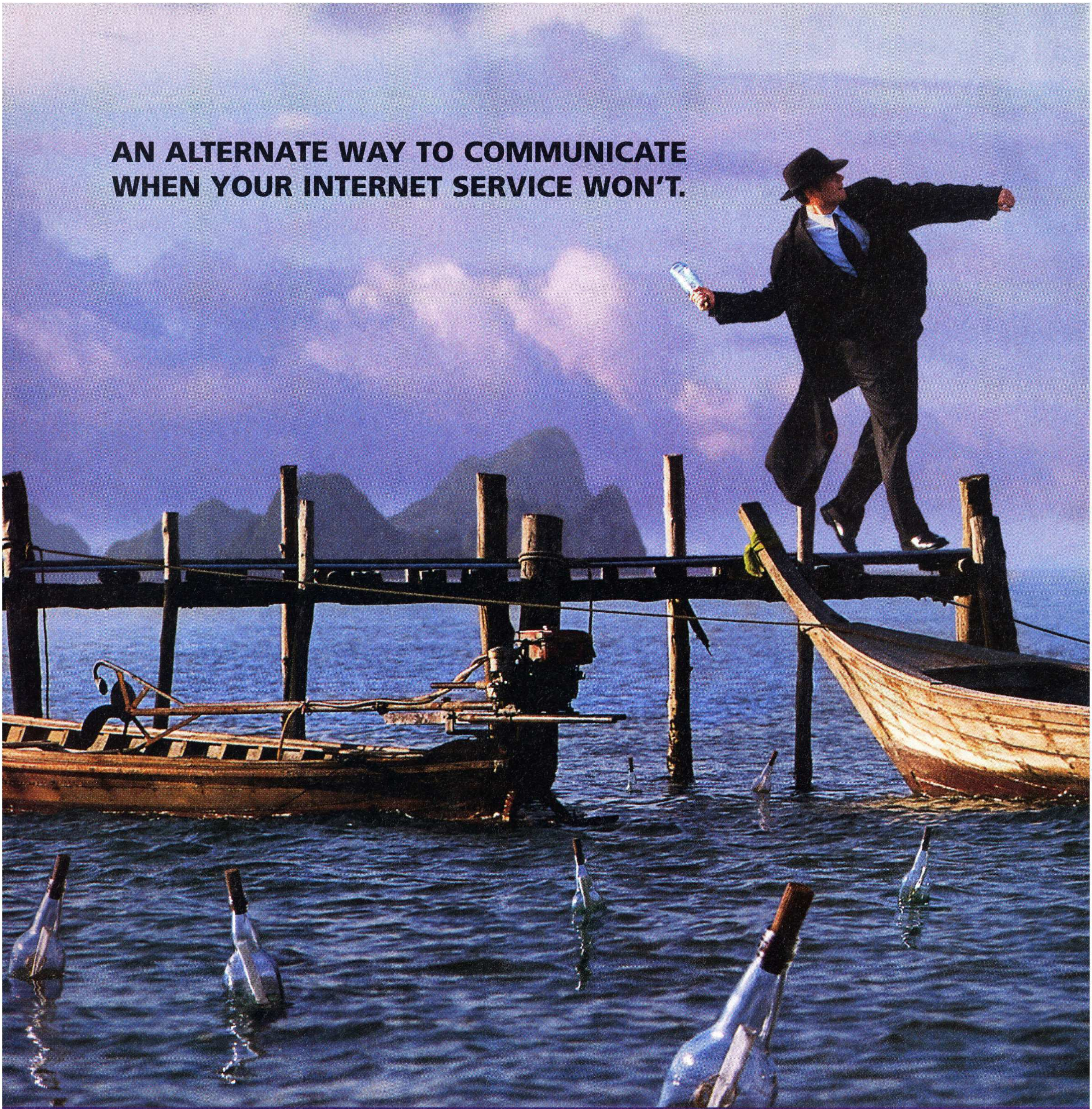

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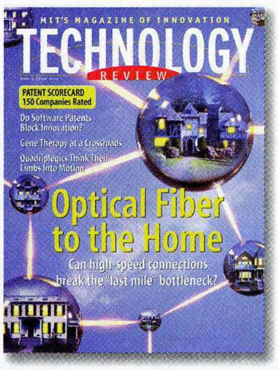
"Web-based commerce was starting to shape up as the great equalizer. Now it is once again only for the big guys."

Patented Thoughts?

THANK YOU FOR PRESENTING SUCH A lucid collection of articles about IP and the uninspired state of the Patent Office. As an engineer, software developer and consultant, I can already imagine paying royalties to the estates of Newton, Gauss, Euler, Turing, Licklider and other luminaries every time we take a derivative of a function, use the normal distribution curve or write a computer program—*not.* I'm surprised the Patent Office didn't grant a patent to Walker Digital on the process of creative thinking.



Web-based commerce was starting to shape up as the great equalizer whereby the little guy with a smart idea could make it. Now it is once again only for the big guys that can afford armies of legal counselors. Too many times I've seen small companies walk away from opportunities even at the mere threat of a lawsuit. They just don't have the resources to fight. In the long term, this lack of vision from the Patent Office will have negative impacts on upstarts and commercial creativity. As with monopolies, we will all lose.

ALFRED KAUSEL
Clearwater, FL

AS A LONG-TIME IP LAWYER, I GREATLY appreciate the public service your latest issue has provided by extensive articles on intellectual property law, especially internet-business related patents. I think a few additional points should be made:

First, the United States has the patent system it pays for. The U.S. public is not willing to spend several thousand dollars extra for a thorough prior art-search and examination of all of the more than 220,000 patent applications a year. Do the arithmetic—it's real money. So we have what the public, via Congress, has been willing to pay in patent fees—a system in which the norm is a single young patent examiner, with some technical, but no legal, education, allowing a patent application after only about six to 10 total hours available for examining it.

Another point not to overlook is that there is a very low-cost alternative to patent litigation: reexaminations. Reexamination can be requested for any U.S. patent, at any time, by anyone, with a simple document and a fee. But you have to do more than kvetch! You have to submit relevant patents or publications earlier than the patent's filing date.

Last but not least, without effective IP protection, any "me-too.com" can enter a business and take it over or destroy the profit margins. Thus, a key public benefit of IP protection by patents is supporting venture capital investments in new businesses.

PAUL F. MORGAN
Rochester, NY

Bloated Middle

FUNNY HOW FAST LEONARDO CHIARIGLIONE'S concerned plea, "How can an artist earn a living?" was answered by those knights in pinstripes from the Secure Digital Music Initiative, "a nonprofit organization with 150 corporate members." ("The Value of Content," *TR* March/April 2000.) Corporate members! Nonprofit? Shame. Could it be that the bloated middle between artists and music consumers contributes to the feeling that copying a $23 CD onto a 99¢ CD-R is only cheating the artist a nickel? Blame the Grateful Dead for allowing free taping and trading of their live performances, and the band's business philosophy of "self-ownership," for a 30-plus-year "dangerous example" that artists can achieve financial success without handlers in suits. Chiariglione's appeal is a lot less about the beret-wearing romantic that should proudly starve "dignified and penniless" than about the concern of locking down the power of the industry status quo.

CLAY D. ROACH
Network Services Specialist
The University of Georgia Tifton Campus
Tifton, GA

LEONARDO CHIARIGLIONE'S ANALYSIS OF THE current impasse between the "open-source-all-things-on-the-net-should-be-free" thinkers and the traditional distributors of intellectual property, entertainment and other products of the mind is right on the money. When the two extremes come to the middle ground where buyers pay only for content and distributors give up claims to high prices based on the old system of reproduction and distribution, we will have a working system. Sought-after artists will be more accessible and hence better paid. Perhaps distributors will go by the wayside, but I think not. There will always be people who do a better job of selling a product than the creator can, and they will earn a slice of the pie. The key to an equitable system is held by Web technologists. It seems that Chiariglione sees his role very clearly; he and others like him must facilitate fair exchange.

JIM LEWIS
Roxbury, MA

CHIARIGLIONE'S COLUMN MAKES THE PRESENT situation as clear as possible, but I think we are in for a long tense transition time while the fat cats duke it out over standards and rules. Just keep creating!

PETER MOFFITT
Brooklyn, NY

THE BIGGEST PROBLEM WITH CREATING pay-per-view systems in a digital world is that consumers are already aware that technology exists (or will soon exist) to make pure digital copies of the media they crave *without* payment. Why should I want SDMI when MP3 works just as well without studio intervention? Consumers will accept pay per view in the arenas where they've already come to accept it, such as one-time events or broadcasts, or a first-run movie theater ticket where the entry price includes a seat, some ambiance and

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maybe your shoes sticking to the floor. Extending pay per view to media that consumers enjoy multiple times, such as music, where free access has been the norm, seems hopelessly overbearing.

SAM POSTEN III
SW Engineer, Ilex Systems
Navesink, NJ

THE CRUCIAL ISSUES, AS I SEE THEM, WERE left untouched in Chiariglione's column. Will SDMI provide the means for artists to negotiate transactions without a third party? Or will some part of SDMI be kept proprietary for the purpose of subsidizing an otherwise unnecessary middleman?

WALTER SARGENT
Huntington, NY

I BELIEVE THAT ALL ATTEMPTS TO MAKE A secure digital music format will fail. New users will be unwilling to embrace a format that excludes the majority. Another reason SDMI is doomed is that home programmers would bypass or hack these secure formats easily, rendering them useless, or create their own comparable or more efficient formats. With today's computer-literate populace, viable alternatives to unpopular standards will remain commonplace. And SDMI is not favorably looked upon because it shows the increasing trend toward subsidization and regulation of computers and the Internet. If one type of content is priced, what prevents any other types of data to be taxed as well? Will word processors charge 15 cents per page of text? Will Adobe Photoshop require you to pay for "virtual" paint and pencils?

CAMERON CHRISMAN
Nevada City, CA

CHIARIGLIONE WRITES: "WHEN CONTENT can no longer be indiscriminately copied, it recovers its lost value." This is an unattainable goal, since the very act of making content experienceable makes it copyable, regardless of playback method. Even if I can't crack a DVD's encryption, for example, nothing stops me from scanning the electrical levels in my TV set and writing out the RGB pixel values to a storage device. Building elaborate security schemes into PCs and playback devices is not the answer, because technology keeps changing. It's hard enough getting existing software to run properly. We don't need more software on top of it. Chiariglione couldn't say it better himself: "Putting these technologies together is no simple task." He's only talking about MPEG-7 and MPEG-21. I feel safe in saying that he'll never make it.

RAY GARDENER
President, Daylon Graphics
Maple Ridge, British Columbia

Scorecard Controversy

IT IS UNFORTUNATE THAT YOU DECIDED TO publish uncritically CHI Research's patent data, and to make this "Patent Scorecard" a prominent part of an accompanying article ("Companies Squeeze the Patent Pipeline," *TR* March/April 2000).

Among patent practitioners there is controversy about whether these indicators hold any meaning regarding patent portfolio value. The "current impact index" and the dependent technology strength indicators are based upon the number of current-year patents citing a company's patents of 5 prior years. A frequently cited patent is supposedly more valuable that one infrequently cited. This is based upon a false assumption regarding citation. A patent includes two parts. The first is a description of how to make and use the invention. The second part is the claims, which form the legal definition of the rights granted. Citation in a later patent is based upon the description and not upon the claims. Thus citation frequency measures something that may be only weakly tied to the actual merit of the patent.

The technology strength indicator is dependent upon a second unsound premise that individual patent values are linearly additive. That is, it assumes that having two patents is twice as valuable as having only one. This assumption may not hold for patents to related inventions, which may overlap. The value of even unrelated patents may not be linearly additive due the differences in the value of the market for the goods or services within the scope of these patents.

ROBERT D. MARSHALL, JR.
Garland, TX

CHI Research responds: *When a patent is issued, it carries on its front page a list of all the previous patents that the inventor and patent examiner believe may limit its claims. It is correct that these references are made to the earlier patents in their entirety, not only their claims. This would be a problem if the overall content of large numbers of patents differed markedly from the content of their claims. However, we are not aware of any evidence showing this to be the case on a large scale.*

As to Marshall's claim that the value of patents is not linearly additive, this is an issue of sample size. Most statistical measures rely on certain sample sizes in order to be robust. CHI agrees that a company with two patents is not necessarily stronger than a company with one patent. However, the Patent Scorecard is dealing with companies with large numbers of patents. CHI is therefore happy to stand by a technology ranking that places IBM above NEC, on the basis that it has twice as many patents in 1999, and these patents are more highly cited.

Toxic Tort

WOULD YOU MIND EXPLAINING JUST WHAT Jeff Hecht meant when he wrote: "Mom is upstairs working, using telepresence to control a robot cleaning up a toxic waste site in New Jersey." ("Fiber Optics to the Home," *TR* March/April 2000.) I can only assume that you meant to suggest that New Jersey is a world leader in the application of high technology to the problem of cleaning up hazardous wastes. Surely a magazine of *Technology Review*'s stature is not perpetuating stereotypes. When such regrettable things happen, one possible use of the new home-based broadband technology would be to send multiple copies of angry letters to insensitive writers.

KEVIN OLSEN
Wayne Township, NJ

Hecht responds: *The Garden State owes its considerable prowess in toxic cleanup to large volumes of experimental material generously provided by generations of long-vanished local industries, and by New Yorkers who kindly contributed their garbage to fill New Jersey wetlands. It is hardly alone among older industrialized states, and though its rivers may not be crystal-clear, none has ever caught fire and the state is cleaning them up.*

Mary Contrarians

HOW IS MARY MEEKER EARNING $15 MILLION last year any different than the millions earned by NBA, NFL or MLB players ("Not Com," *TR* March/April 2000)? How about the compensation packages earned by the CEO's of America's corporations, which in many cases are several multiples of Mary's

$15 million? G. Pascal Zachary might want to go back to the basics of economics and marketing. Compensation is a function of the perceived value of the function provided. Certain skills are valued differently by the market. Shouldn't an ER physician or a policeman who puts his life on the line every day to protect others be paid more than a silver-tongued maven of the Internet? In a perfect world, maybe so, but in her own way, Mary has embraced the revolution known as the Internet, taken advantage of it, and made herself, Morgan Stanley and countless millions a few bucks along the way.

Ed Gonsalves
Director of Sales and Marketing
North America
Smart Link
Watertown, MA

G. PASCAL ZACHARY'S *AD HOMINEM* ATTACK on Mary Meeker was disgraceful. Shame on you for publishing this trash. Zachary could have articulated his concerns about the marketing of technology stocks without demonizing an individual.

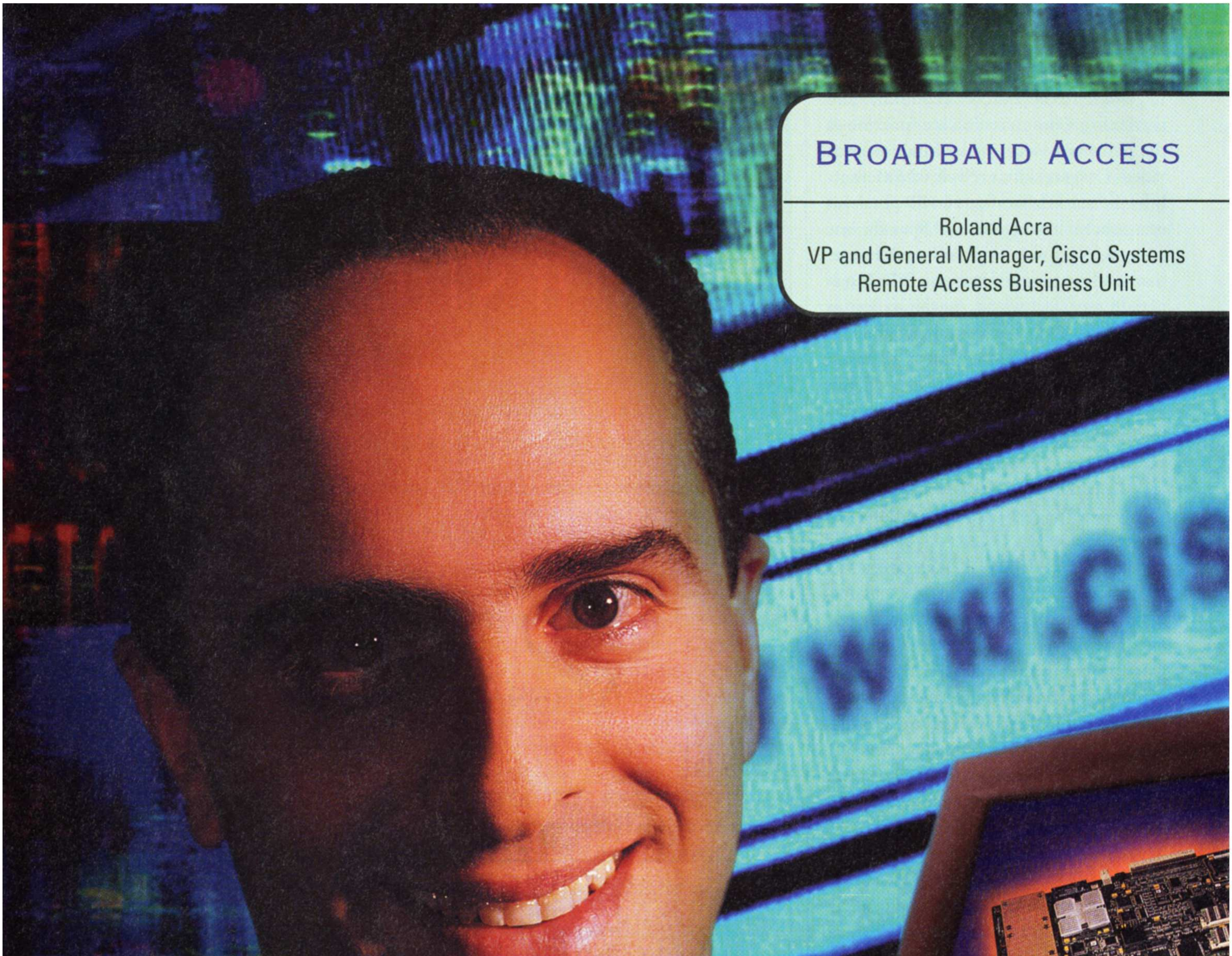
Richard Greenspan
Newton Center, MA

Erroneous Energy

"POWER PICKS" IN THE MARCH/APRIL ISSUE stated that electricity generated from coal, nuclear and oil total 66% of California's power consumption. The correct figure for 1998 (most recent complete statistics) is about 36%—coal 20%, nuclear 16% and oil 0.1% (see www.energy.ca.gov/electricity/system_power.). About 32% of the power was from natural gas-fired plants. Most of these plants historically had the ability to burn either oil or gas, and therefore are sometimes loosely, but misleadingly, referred to as oil/gas-fired plants. However, oil use in these facilities in most years is insignificant. I believe the 66% figure quoted in your article resulted from erroneously attributing the "oil/gas" plants to oil, rather than gas.

Kenneth Wilcox
California Energy Commission
Sacramento, CA

The editors respond: *Mr. Wilcox's numbers are right. In Greenmountain.com's profile of California, the company points out that some 31% of the state's energy is derived from natural gas. We regret the error.*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DSP
TEXAS INSTRUMENTS TECHNOLOGY

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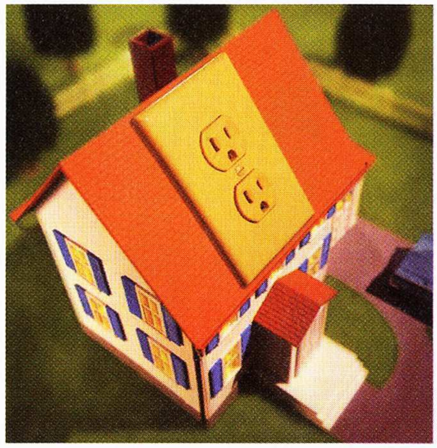
*International Data Corp. †Forrester Research, Inc.

D S P A N D A N A L O G

TEXAS INSTRUMENTS

Thick and Thin

To avoid rust or flaking, the paint on a car must have a thickness consistent to within a fraction of a millimeter. Auto makers test thickness by picking a sample car, waiting until it's dry, and hitting it with an ultrasonic pulse from a handheld meter. But that process is slow and expensive—and now its days may be numbered. DaimlerChrysler is testing a laser inspection technology that works on wet paint. Designed by Plymouth, Mich.-based Perceptron, the system spits out several hundred laser pulses one after the other. Each infrared burst produces an ultrasonic "ring" that is higher in pitch where the paint is thinner. One big advantage of this system is that the line can be stopped and a problem fixed before a hundred or more mis-painted cars have gone through drying ovens. The National Institute of Standards and Technology, which funded Perceptron's development work, estimates that the system could shave $50 off the cost of painting each car, saving the Big Three automakers hundreds of millions of dollars a year.

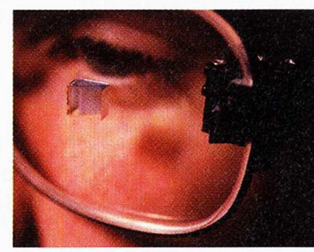


VITO ALUIA

Fuel Cell House

A Latham, N.Y., company wants to put a power plant in your backyard. Plug Power is testing a residential fuel cell system in a proof-of-concept home. The house taps into the natural gas distribution network, processing the gas into a hydrogen-rich stream that combines with oxygen in the air to drive the fuel cell's chemical reaction. The system generates electricity for 7 to 10 cents per kilowatt-hour (on par with utility prices) and emits only carbon dioxide, water and heat (which can be recycled to warm the home's air and water). The refrigerator-size unit converts 40 percent of the gas's energy into electricity, providing all the power for the 3-bedroom test home. Merrill Lynch analyst Sam Brothwell has been watching Plug Power and sees "tremendous potential." He predicts early adopters will get their hands on these systems in 2001 or 2002.

Remembered Spectacles



UNIVERSITY OF ROCHESTER

At age 60, 1 in 20 people suffer from cognitive impairment or memory loss. By age 85, it's 1 in 3. Until there are good therapies for reversing these deficits, we'll need ways to remind ourselves of what we might otherwise forget. One unlikely source of such reminders in the future might be eyeglasses. Specs being developed by a collaboration of the University of Rochester's Center for Future Health and the MIT Media Lab could aid a forgetful wearer by sensing patterns in the environment and displaying or whispering a prompt such as: "The person you're looking at is your son-in-law." Randal Nelson, at the Rochester center, has built glasses with built-in sensors and display. By this summer, he expects to take the next step: integrating the glasses with pattern-recognition software.

Instant Digital

Digital cameras are hot, and they're certainly the way to go when you want to put your photos on the Web or attach them to an e-mail. But at consumer prices, old-fashioned film still provides a much sharper picture—as well as gives you a snapshot to hold within seconds of tripping the shutter.

Starting in August, you will be able to get the best of both technologies in one package. That's when Polaroid plans to roll out a camera that, for the first time, brings instant and digital photography together. The new product—the I-Zone Pocket ComboCamera—will join a 640x480 pixel digital camera to an instant camera that takes photographs on Polaroid's smallest format film (about 2.5 centimeters square). The result: You can share the instant paper image now while keeping the digital copy for easy electronic storage and online distribution. Incorporating an inexpensive semiconductor image sensor, the camera will sell for about $100.

DICK LOMBARDI/POLAROID

Clean Meat

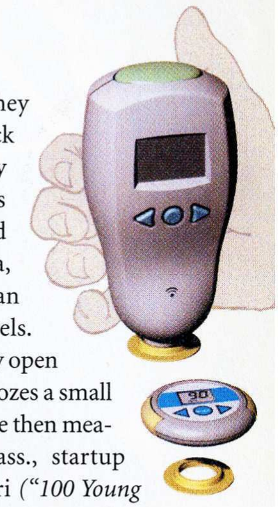
Each year, thousands of people in the United States get sick and dozens die from eating undercooked meat tainted with *E. coli* bacteria. A quick, inexpensive test in development at Texas A&M University could help ensure safe meat products. Today's methods of bacteria detection sample only portions of raw meat, says food scientist Douglas R. Miller. He and colleague Jimmy T. Keeton have what they think is a better idea: Detect the germs indirectly by measuring the levels of specific meat proteins after cooking. If meat has been cooked at a high enough temperature to kill the bacteria, these proteins should denature, losing their structure and function. Testing for denatured proteins requires only a drop of meat juice on a test strip. Within minutes, a color change shows the "safety" of the meat. Morningstar Diagnostics, a Roseville, Calif., maker of diagnostic tests, plans to license the technology.

Antibiotics, Heal Thyself

Every year, more than 20 million kilograms of antibiotics are released into the environment in human and animal waste. Manure from antibiotics-fed farm animals, for example, is often spread on fields. These releases are an important factor in the development of new strains of antibiotic-resistant bacteria. To attack the problem, chemists at Wayne State University have synthesized an antibiotic that chemically self-degrades after several hours of exposure to light.

Wayne State researcher Shahriar Mobashery calls this the first example of an "antibiotic that destroys itself." Mobashery attached a nitrogen-containing chemical group to a *beta*-lactam antibiotic, the most commonly prescribed class of antibiotics. This compound itself will probably not become a drug. But Mobashery says the test should be food for thought for pharmaceutical companies looking to slow the spread of bacterial resistance.

Sounds Painless



TOM DEVLIN

Diabetics look forward to the the day when they will no longer have to endure the painful prick of a needle for drawing blood. That day may just have drawn nearer. A team of scientists including chemical engineers from MIT and the University of California, Santa Barbara, have completed the first human tests on an ultrasound device for testing blood sugar levels.

The device uses sound waves to temporarily open up tiny pores in the skin, out through which oozes a small amount of fluid; sugar levels in that the fluid are then measured. Sontra Medical—a Cambridge, Mass., startup launched by UCSB engineer Samir Mitragotri *("100 Young Innovators,"* TR *November/December 1999)* and several colleagues—expects to have products ready in three to five years. One possibility: a wrist-watch like device that monitors blood glucose and, when needed, delivers insulin directly through the skin.

Watching Over You

VITO ALUIA

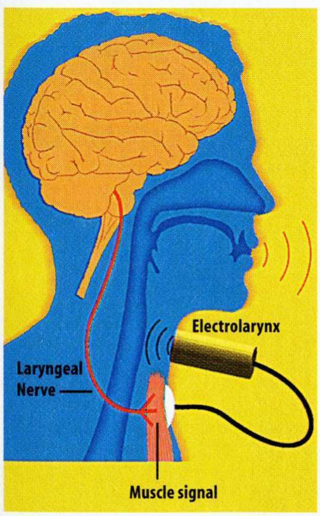
It was the brainchild of a retired police officer—a coin-sized, implantable global positioning system (GPS) transceiver that could help authorities locate an abducted child. The cop patented his idea in 1997, and now Palm Beach, Fla.-based "e-business provider" Applied Digital Solutions (ADS) has acquired rights to the somewhat Orwellian invention, which the company has dubbed "Digital Angel." Equipped with both GPS and biological monitoring capabilities, the Digital Angel could, in theory, not only find a lost child but also alert a local hospital when an elderly patient experiences cardiac arrest while at home. ADS intends for the device to derive its power from normal muscle movements, eliminating the need for a battery.

ADS is working on a $130 million deal to acquire Destron Fearing—a South St. Paul, Minn., maker of identification devices for pets, livestock and wildlife—and merge that company into a Digital Angel.net subsidiary. Preliminary testing of a Digital Angel prototype could begin by year's end.

Sharper Spacecraft

Today's materials have limited capacity to withstand heat, forcing aerospace engineers to design spacecraft like the space shuttle with blunt noses and wing edges. Such shapes allow a layer of compressed air to form above the surfaces as the craft reenters the atmosphere—lowering the heat load but also making the craft less aerodynamic. A new ceramic, developed at NASA's Ames Research Center, might make possible spacecraft with sharper edges and pointed noses that slice through the air on their way to and from orbit. The ceramic withstands temperatures up to 2800 degrees C (today's shuttle begins to sizzle at 1500 degrees). In a June test, fins made from the material will be attached to the nose of a Minuteman missile.

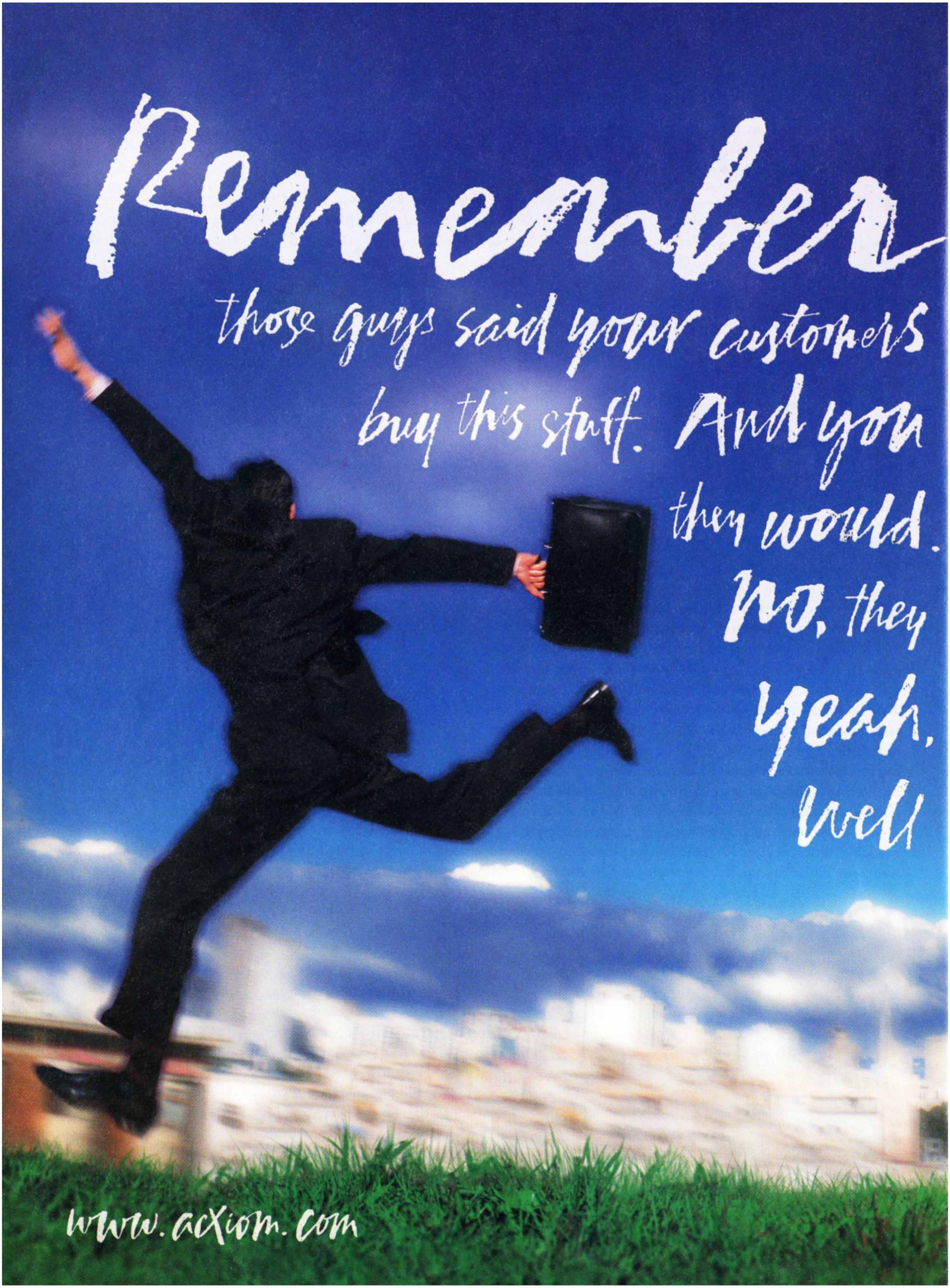
Voice Box

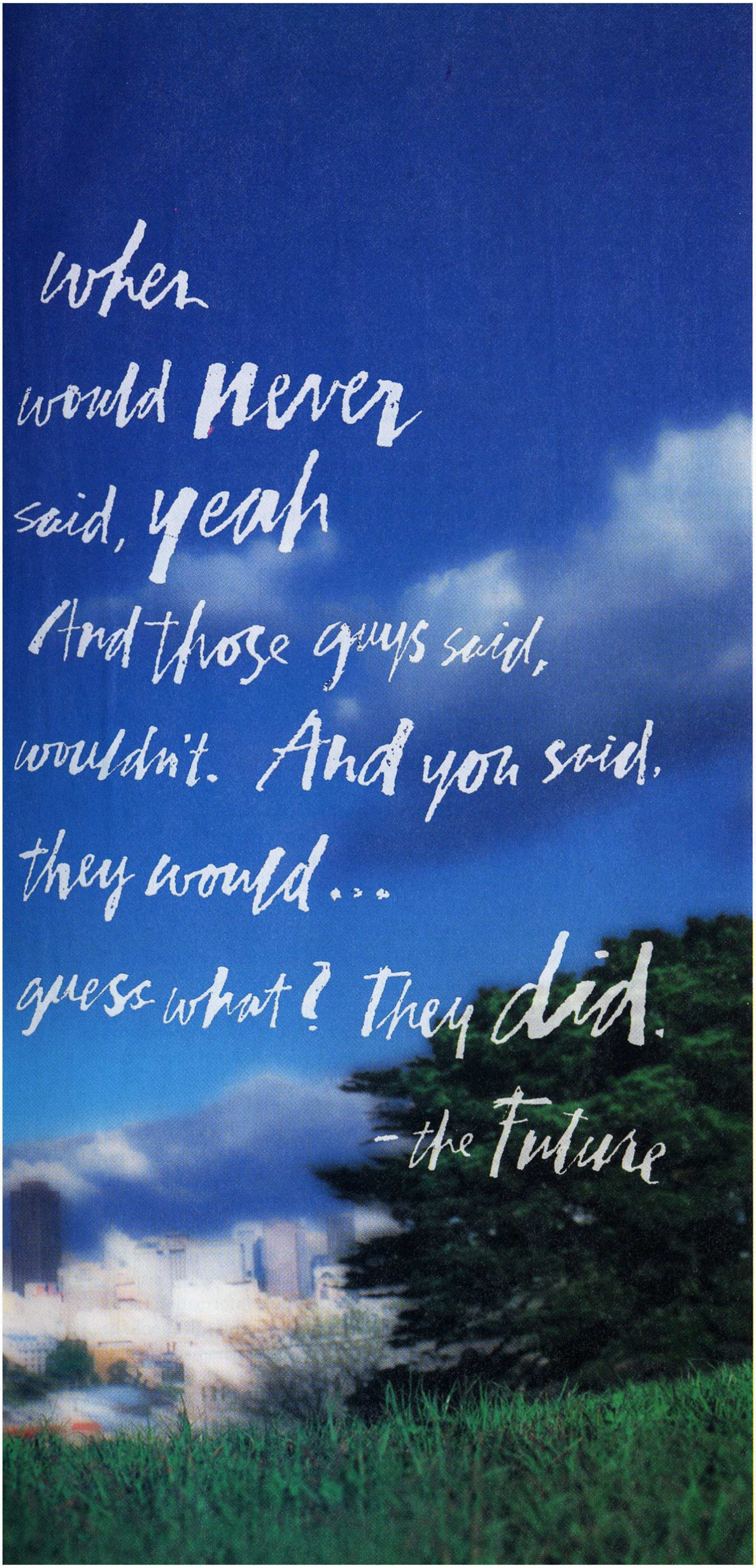


BETSY HAYES

Have you ever heard a strange robotic voice, then turned to see someone speaking through an electrolarynx? For victims of laryngeal cancer, a buzzer pressed to the neck restores speech by stepping in for lost vocal cords, but produces machine-like sounds that can be hard to understand.

In an effort to restore natural pitch and control, Massachusetts Eye and Ear Infirmary researchers are developing an electrolarynx commanded by the same nerve signals that normally control the voice. The strategy is to attach laryngeal nerves to small muscles in the neck, then use electrical signals from those muscles to turn the electrolarynx on and off and control its frequency. Doctors have re-routed nerves in nine patients so far. Project leader Robert Hillman says neural control would allow hands-free operation of the electrolarynx. Eventually, the entire system could be implanted.


Remember
those guys said your customers
buy this stuff. And you
they would.
No, they
yeah.
well
www.acxiom.com


When
would never
said, yeah
And those guys said,
wouldn't. And you said,
they would...
guess what? They did.
-the Future

Speech and Vision

After 40 years of humans serving computers, people are finally beginning to wake up and demand that the relationship be reversed: They want machines to become simpler, address human needs and help increase human productivity. That's as it should be. With computer technology maturing, it's high time, as we have repeatedly said in this column, for makers and users of computers to change their focus from machines to people.

But how do you make a machine simpler? With fewer controls? Not really. As you know from watches and other devices that have one mode-changing button and another to select functions within a mode, you can easily get lost in a confusion of modes and functions. Would machines be simpler if they had fewer capabilities? No! Imagine a car that can only do two things—go and turn right. This car can go anywhere, but you wouldn't prefer it to your own car, which has more capabilities. What is it that we really want when we ask that our computers be easier to use?

Future computers will combine these modalities to communicate much more naturally than current models can.

True ease of use, as opposed to the perfunctory use of colors and floating animals to create the illusion of "user friendliness," involves means of interaction that are natural to people and therefore require no new learning. Speech and vision are the two principal means we have used to interact with other people and the world around us for thousands of years. That should be enough of a clue to steer our attention to these two modes of interaction. And since vision occupies two-thirds of the human cerebral cortex, we may be tempted to declare it the queen of human-machine communication. That would be an easy—but deceptive—conclusion.

Vision and speech do not serve the same natural roles in communication. Being Greek, I can still hold a "conversation" in Athens, through a car window, using only gestures and grimaces—one clockwise rotation of the wrist means "how are you" while an oscillating motion of the right hand around the index finger with palm extended and sides of mouth drawn downward, means "so-so." A sign language like ASL works even better. But when speech is available, it invariably takes over as the preferred mode of human communication.

That's because among people, speech is used symmetrically for transmitting and receiving concepts. Visual human communication, on the other hand, is highly asymmetric—we can perceive a huge amount of information with our eyes, but can't deliver equally rich visual information with gestures (visual communication would be more symmetric if we all sported display monitors on our chests). The power of vision in humans lies primarily in the one-way digestion of an incredible amount of information—nature's, or God's, way of ensuring survival in a world of friends and enemies, edible and man-eating animals, useful and useless objects, lush valleys and dangerous ravines, where maximum information was essential.

But then, why didn't nature, or God, make speech just as asymmetric as vision? I'll venture the guess that speaking and listening were meant for intercommunication rather than perception, where, unlike survival, symmetry was desirable. And since survival was more important than chatting, the lion's share of the human brain was dedicated to seeing.

These conclusions run against the common wisdom that for human-machine communication, "vision is just like speech, only more powerful." Not so! These two serve different roles, which we should imitate in human-machine communication: Spoken dialogue should be the primary approach for back-and-forth exchanges, and vision should be the primary approach for human perception of information from the machine.

We can imagine situations where a visual human-machine dialogue would be preferable, for example in learning by machine to ski or juggle. But we are interested in human-machine intercommunication across the full gamut of human interests, where, as telephony has demonstrated, speech-only exchanges go a long way. (Might these basic differences between speech and vision have contributed to the lack of success of video telephony?)

Finally, if we can combine speech and vision in communicating with our machines, as we do in our interactions with other people, we'll be even better off. But that's not easy to do yet, because the technologies for speech and vision are in different stages of development. Nor is the wish to combine them reason enough to ignore their different roles.

Conclusion: When you face a machine, instead of your surrounding world and other people, your interactions will be comparably natural, and the machine easiest to use, if it uses speech understanding and speech synthesis for two-way human-machine dialogue (these technologies have begun appearing commercially), and if it has large realistic displays that convey to you a great deal of visual information (as do today's displays). As machine vision improves, it should be combined with speech for even more natural human-machine exchanges (such combined capabilities are now being researched and demonstrated in several research labs).

So, take heart: Simpler, more natural computer systems will enter our lives within the next 5 to 10 years. Let's speed up their arrival, as users by asking for them, and as technologists by daring to build them. ◊

WORLD WIDE WEB

Seeking Smarter Searches

New search engines could bring order to the Web

IT'S THE ONLINE ORDEAL EVERY WEB surfer dreads: You type a simple question or keyword into an Internet search engine only to get the response "about 52,839 pages found." Then it's time for the real searching—as you plow through the hits one by one.

As the amount of information on the Internet explodes, conventional search engines are struggling to keep up. But that's creating lots of opportunity for innovative Net-preneurs who have begun introducing a host of strategies to make searching the Web a whole lot more productive.

JAMES YANG

For instance, at ESPN's National Collegiate Athletic Association (NCAA) men's college basketball site, users can type in "Who won the 1999 NCAA championship?" and get the immediate response: "The University of Connecticut." ESPN's search is powered by Fact City, a 1999 Waltham, Mass., startup that bills itself as the Internet's only "fact-finding engine."

Fact City works by aggregating data sources ranging from the U.S. Census to the Internet Movie Database. When a user asks a question, Fact City uses keywords from the query to find the right database, then the right answer. The scheme relies on a large vocabulary of pre-selected keywords: over 500 alone for the college basketball database, which went live on ESPN in mid-March.

Unlike the Web's original search engines, Fact City doesn't plan to become a multipurpose portal designed to draw millions of Web users. "Our business plan is not to be a destination site," says company vice president Mike Olfe, "but rather establish partnerships with portals."

Ambitious startup companies with better search methods could challenge the Net's most entrenched players, including Yahoo!

Other startup companies, like Why.com of Cambridge, Mass. think better search methods could let them vie with entrenched players such as Yahoo!, the Internet's most trafficked site.

Yahoo!'s experts have spent thousands of hours categorizing the Web into a helpful hierarchy of topic areas and top-rated sites. But Why.com thinks it may be able to outdo Yahoo! with the help of millions of everyday infonauts.

When the service launches this summer, visitors to Why.com will be able to rate Web sites themselves—giving grades on overall quality, as well as for specifics such as design and ease of use. Sites with the highest ratings will get top-billing in their respective categories.

Eventually, Web surfers will be able to further customize the rankings by giving scores from some people greater weight than others. "You'll be able to not only rate sites, but rate other people's ratings," says Sean Carmody, the 20-year-old president of Why.com, who followed in Bill Gates' footsteps by taking a leave of absence from Harvard to co-found the company with two classmates last fall. Carmody says Why.com will also sell research reports to Web sites based on the user feedback.

Observers say the new entrants could force first generation portals like Excite and AltaVista to change how they search the Web. "They have made improvements," says Danny Sullivan, editor of the online publication *Search Engine Watch*, "but a lot of work needs to be done, and there hasn't been as much pressure to do it before now."

Still, better search features may not necessarily be the secret to Internet success. Sullivan points to iWon.com, one of the fastest-growing new search engines, whose success is based primarily on daily cash giveaways of $10,000. "Compelling search is not the best way to attract people," says Sullivan.

—Jeff Foust

SEMICONDUCTORS

Light Fantastic

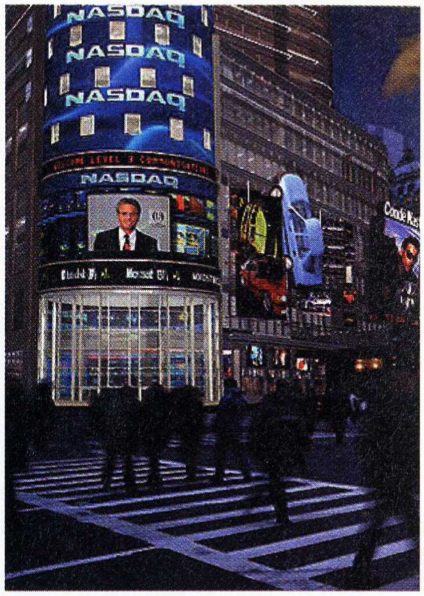
Blue LEDs light up consumer markets

THE INCANDESCENT LIGHT BULB IS A hot technology in one sense—it wastes 90 percent of its energy in heat. Now, experts say, the 122-year reign of the tungsten filament may be coming to an end. Taking its place is gallium nitride, a super material that's set to make billion-dollar waves in consumer markets from lighting to home entertainment.

First formulated more than 70 years ago, gallium nitride is a semiconductor that emits an intense blue light when electricity is passed through it. In the early 1990s, researchers at Japan's Nichia Chemical Industries were the first to master the material, turning it into bright, long-lasting light-emitting diodes (LEDs) of any color. Now, gallium nitride LEDs are finding their way into traffic lights, huge display signs, and the tail lamps of the 2000 Cadillac DeVille.

Although these solid-state lights still aren't as bright as incandescent bulbs, they consume just one-tenth the power and can last 100 times longer. That's why lighting giants General Electric, Philips and Siemens are racing to turn out LEDs for home use by consumers. Together with Agilent Technologies, Philips is spending more than $150 million on its effort, known as Lumileds. "In the future, it is entirely possible that all our room lighting will use gallium nitride light sources," predicts Gerhard Fasol, director of Eurotechnolgy, a high-tech consultancy in Tokyo.

Beyond better bulbs, experts say compact blue lasers made from gallium nitride will soon quadruple the amount of movies, music and data that can be packed onto optical discs such as DVDs. Nichia and Sony are leading the way with a plan to produce new CD players by 2001.



SACCO UK LTD

Gallium nitride LEDs light up a billboard in New York City's Times Square.

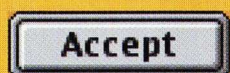
Together, blue lasers and LEDs should drive the market for gallium nitride devices from $400 million today to well over $1 billion by 2006, according to Henry Rodeen, a consultant with Strategies Unlimited, a San Francisco research firm.

—David Wilson

SOFTWARE

Click on the Dotted Line

Here's a little secret: Although you may think you own the software that you have paid good money for, you don't.



Under the provisions of those fine-print contracts that you probably toss in the trash or banish from your screen with a heedless click on an innocuous looking "Agree" button, your tender of cash for *Doom* or *Microsoft Word* gets you only a *license*—under terms dictated by the software's maker.

Although such "shrinkwrap" and "click-through" contracts don't currently carry much weight, a law under consideration by state governments could give these ephemeral agreements legal heft—and give software companies the power to enforce controversial new provisions.

The law in question, the Uniform Computer Information Transactions Act (UCITA), is an extension of the Universal Commercial Code—the framework of rules that underlies state laws governing buying of goods and services. According to Keith Kupferschmid, a lawyer with the Software and Information Industry Association, UCITA would "make sure that shrinkwrap and click-through licenses are uniform and enforceable in all 50 states—and that's a consumer benefit."

But critics say UCITA goes too far by giving statutory weight to broad disclaimers designed to shield software makers from virtually any responsibility for faulty products. Worse, UCITA-sanctioned contracts could forbid licensees from publicly criticizing software—a provision that might stop savvy users from reporting product bugs and security holes over the Web. The new law would "make these crazy terms enforceable," says Skip Lockwood, director of 4CITE, a Washington, DC. anti-UCITA coalition.

Industry proponents admit the law isn't perfect, but argue that the courts can fix objectionable consequences. But with Virginia already signed onto UCITA as of March, and Maryland ready to vote this spring, policy analyst Dori Kornfeld of the Association for Computing Machinery says opponents aren't ready to click "Agree" just yet. "If there are problems," she says, "the time to fix them is now—before the legislation is passed."

—Herb Brody

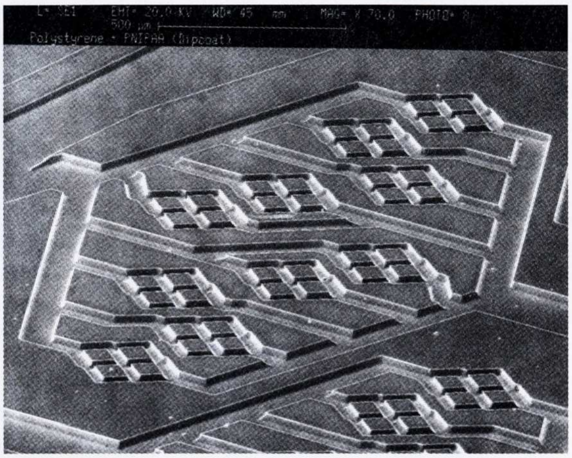
BIOTECHNOLOGY

Blood from a Chip

Bioengineers grow a circulatory system on silicon

THANKS TO ADVANCES IN TISSUE ENGINEERING, doctors can now replace burned skin or worn out cartilage with lab-grown replacements. But engineering larger body parts, such as desperately needed livers, remains out of reach—in part because there's no way to keep these tissues fed with blood. Although a patient's own blood vessels can penetrate and sustain a skin graft, they can't grow fast enough to keep a mass of liver cells alive. "You get cell death before the vessels arrive," says pediatric surgeon and tissue engineer Joseph Vacanti of Massachusetts General Hospital.

Now Vacanti and his partners in the Center for Innovative Minimally Invasive Therapy—a Boston-area research consortium—may have solved that problem with a primitive circulatory system grown on a silicon wafer. The team first used photolithography to etch a template of interconnected veins, arteries and capillaries onto the wafer. Then they seeded the template with vascular cells from a rat lung, which spontaneously grew to coat the grooves, breeding a network of blood vessels. Vacanti's team then showed fluids could pass through the vessels.



DRAPER LABORATORY

A template etched on a silicon wafer is used to grow capillaries.

Brian Cunningham, biomedical technology manager at Draper Laboratory in Cambridge, says even the chip's smallest features—10-micrometer-wide capillaries no bigger than a single red blood cell—made an easy target for Draper's micromechanical fabrication experts. Although the prototype packs 23,040 individual capillaries, human-scale organs will require even larger networks.

Vacanti is now busy working out how to use the chip-grown plumbing to create a functioning rat liver in the lab. He says one approach being considered is to build up an engineered organ by layers, sandwiching blood vessels between sheets of blood-cleansing liver hepatocyte cells and tissue-connecting fibroblasts.

While the results are preliminary, Vacanti says he is excited by the prospect of solving tissue engineering's circulatory dilemma: "If this barrier were breached it would open up tissue engineering to virtually any tissue of the body." **—Peter Fairley**

MATERIALS

Memories are Forever

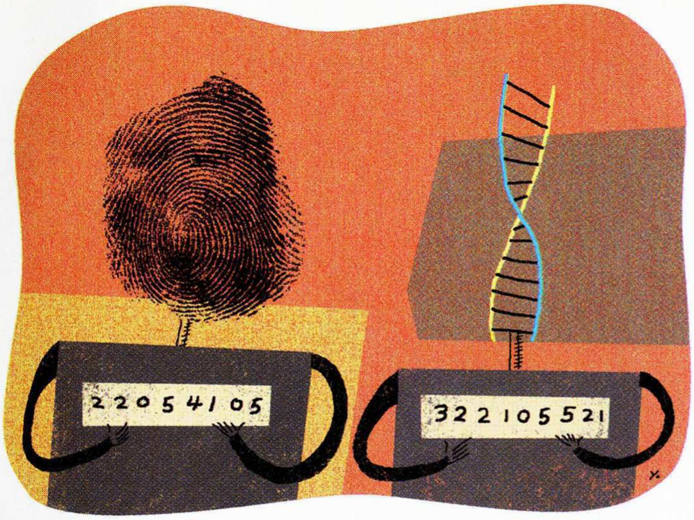
Electrons are fleeting. Magnets remember. That's the reason your computer stores data permanently in a magnetic hard drive, but uses semiconductor electronics for the random-access memory (RAM) that runs software. Problem is, once you cut the juice, the data in this short-term memory disappears. That's why Windows has to re-boot every time—your PC is transferring the program from the hard drive onto the RAM chips.

So it's not surprising that some of the world's largest microelectronics makers are racing to develop magnetic RAM that could provide computers with a fast and cheap "instant on." Scientists at IBM's Almaden Research Center say they have now fabricated a crude magnetic RAM prototype containing 500 working memory cells (each cell represents a bit of memory) by sandwiching aluminum between ultrathin layers of a ferromagnetic metal alloy. The prototype has storage density as good as DRAM (dynamic random access memory), the most common type of semiconductor memory, but reads and writes information 20 times faster while consuming less than than one hundredth the energy.

Although it's still a few years from the market, says Stuart Parkin, an Almaden researcher who helped pioneer recent IBM advances in hard disk technology, magnetic RAM's speed and power efficiency should initially prove "incredibly useful" in battery-operated electronics used for applications such as digital cameras and cell phones. **—David Rotman**

Turning on Magnetic RAM

ORGANIZATION	STATUS
IBM Research (San Jose, Calif.)	Built a 500-cell prototype based on magnetic tunneling junction technology
Hewlett-Packard (Palo Alto, Calif.)	Demonstrated a working test device proving design and materials
Honeywell (Plymouth, Minn.)	Has shown a 1-Mbit chip; promises a product for specialized defense applications by next year
Intregrated Magnetoelectronics (Berkeley, Calif.)	Built a 8-Kbit prototype; plans to complete a 1-Mbit all-magnetic RAM device next year
Motorola (Phoenix, Ariz.)	Demonstrated a 512-bit working prototype; predicts a commercial product within five years



JAMES YANG

FORENSICS

Crime Genes

A DNA mismatch raises fears

ADVOCATES OF RAPIDLY growing databases of criminals' DNA say they're a potent crime-fighting tool with little downside for law-abiding citizens. Typical of this school is Howard Safir, New York City's Police Commissioner, who told the *New York Times* last summer: "We should be collecting [DNA] from everybody. The only ones who have anything to worry about from DNA are criminals."

Well, not quite. British officials admitted in January that robbery scene DNA matched to England's databank of 660,000 genetic profiles of convicts and arrestees had led to the arrest of an innocent man. The odds against two people having DNA fingerprints similar enough to cause such a mismatch are huge—about 37 million to one. Nevertheless, further testing and a string of alibis later proved that police had detained the wrong person.

The false arrest, say privacy and prisoner's rights advocates, highlights ongoing problems with the proliferating criminal DNA databases. The FBI-maintained National DNA Index System (NDIS), begun in 1998, now contains 215,000 DNA fingerprints. Each state already requires prisoners convicted of offenses ranging from murder to intimidating a witness to submit DNA specimens. By the time all 50 states join the national system in 2002, the FBI predicts NDIS will contain more than 600,000 genetic profiles and will be growing at the pace of 100,000 new profiles per year.

The enlargement of NDIS has attracted criticism from civil rights groups, who question the constitutionality of taking DNA from a convict without a search warrant. And privacy advocates fear that geneticists might use the cache of convicts' blood to search for a genetic basis for criminal behavior.

Few existing state or federal laws set clear rules for the fate of the DNA samples, which many states save indefinitely. "It's one of the biggest problems with the system now," says Chris Asplen, director of National Institute of Justice's Commission for the Future of DNA Evidence. "Vague regulations leave the system open to abuse."

Despite these concerns, lawsuits filed to stop DNA databases have not fared well. In a case brought by the Massachusett's public defender's office and the local chapter of the American Civil Liberties Union, the state supreme court ruled last November that a warrantless examination of a convict's genome does not violate the Fourth Amendment's protection against unlawful search and seizure because the resulting DNA fingerprint will be used for "identification" only, a purpose permissible under the constitution.

Still, as NDIS grows, the chance of DNA "misidentifications" will grow, too. "There's a greater chance that you'll find a close match as the databases get bigger," says Paul Bresson, an FBI spokesman.

—Rebecca Pollard

FOLLOWUP

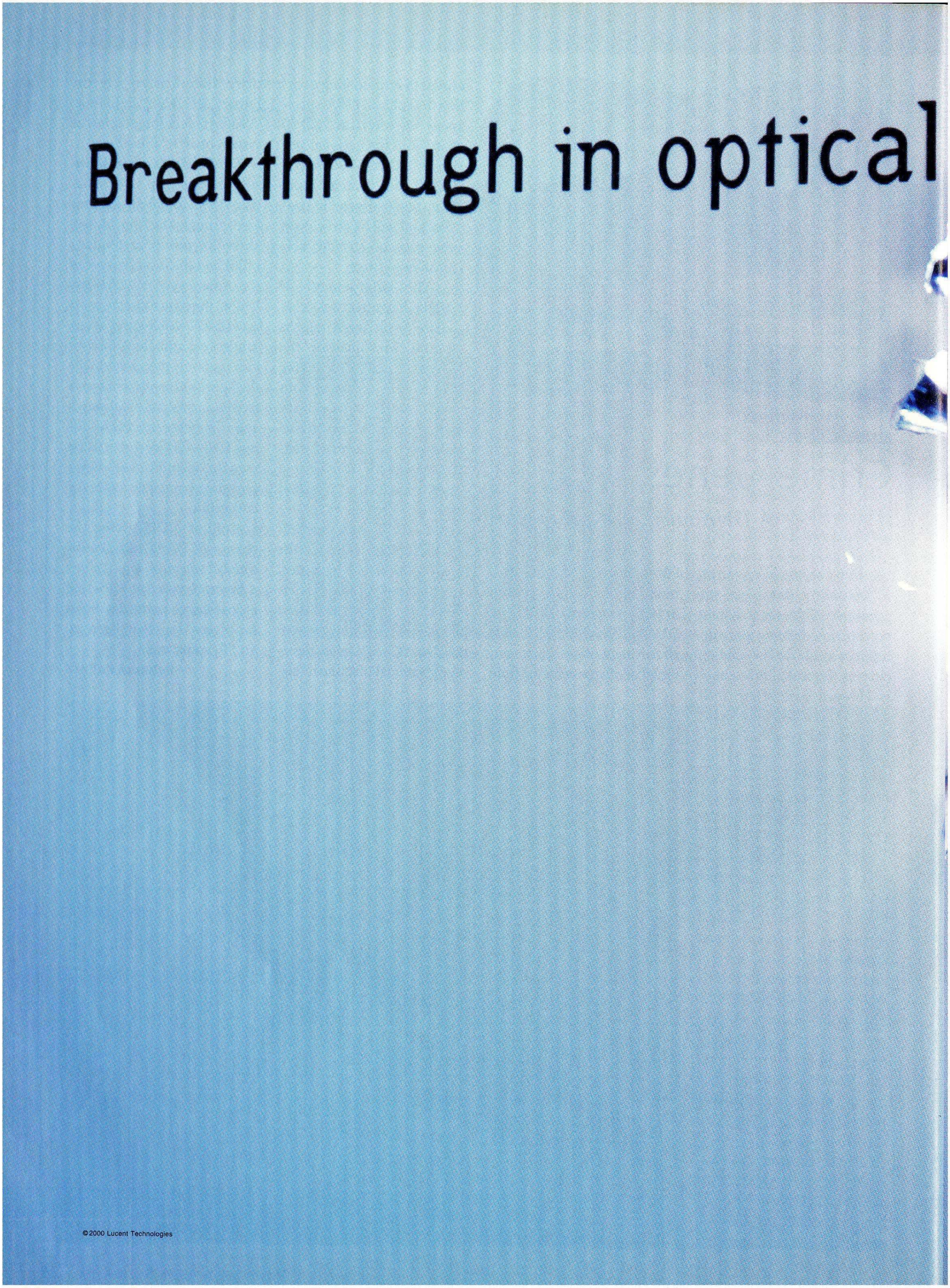
Amazon's Mea Culpa, Good News for Gene Therapy, and Sydney, Ahoy!

■ Will patents on Internet business methods hurt e-commerce? Last issue, *TR* singled out Amazon.com for its troubling patent on "one-click" purchasing. Now, Amazon CEO Jeff Bezos has conceded in a public letter that he's troubled too. In fact, he believes the new wave of e-commerce patents "could end up harming all of us." Although Amazon isn't ready to give up its own intellectual property just yet, Bezos has asked for congressional action. One suggested fix: Make software patents last only three to five years, instead of the usual 20.

■ Last issue, when *TR* profiled the effort by Children's Hospital of Philadelphia's Kathy High to cure hemophilia using gene therapy, the scene was tense. High's field was reeling from the death of a patient, and documented successes were few. In March, however, there was good news. Two hemophilia patients in a small gene-therapy study led by High and Stanford University's Mark Kay had gotten measurably better with unexpectedly low doses. An editorial accompanying the results in the March issue of the journal *Nature Genetics* called the study "exemplary," adding that "it may prove to be the first report of clinically efficacious application of gene therapy to haemophilia."

■ Almost two years ago a novice inventor from Australia told *TR* of his unlikely ambition: to build a solar- and wind-powered, "winged" ferry boat in time to sail Sydney Harbor during the 2000 Olympic "Green Games." Now it looks like Robert Dane and the company he founded, Solar Sailor, are right on course. With the help of corporate and government sponsors, they've built a 21-meter, 100-person ferry, due to be commissioned on Easter Sunday. Tickets for the vessel's first commercial voyages, planned for May, are available at www.solarsailor.com.

—Rebecca Zacks


Breakthrough in optical

Freedom—or Copyright?

Once upon a time, in the age of the printing press, an industrial regulation was established for the business of writing and publishing. It was called copyright. Copyright's purpose was to encourage the publication of a diversity of written works. Copyright's method was to make publishers get permission from authors to reprint recent writings.

Ordinary readers had little reason to disapprove, since copyright restricted only publication, not the things a reader could do. If it raised the price of a book a small amount, that was only money. Copyright provided a public benefit, as intended, with little burden on the public. It did its job well—back then.

Then a new way of distributing information came about: computers and networks. The advantage of digital information technology is that it facilitates copying and manipulating information, including software, musical recordings and books. Networks offered the possibility of unlimited access to all sorts of data—an information utopia.

But one obstacle stood in the way: copyright. Readers who made use of their computers to share published information were technically copyright infringers. The world had changed, and what was once an industrial regulation on publishers had become a restriction on the public it was meant to serve.

In a democracy, a law that prohibits a popular, natural and useful activity is usually soon relaxed. But the powerful publishers' lobby was determined to prevent the public from taking advantage of the power of their computers, and found copyright a suitable weapon. Under their influence, rather than relaxing copyright to suit the new circumstances, governments made it stricter than ever, imposing harsh penalties on readers caught sharing.

But that wasn't the last of it. Computers can be powerful tools of domination when a few people control what other people's computers do. The publishers realized that by forcing people to use specially designated software to read e-books, they can gain unprecedented power: they can compel readers to pay, and identify themselves, every time they read a book!

That is the publishers' dream, and they prevailed upon the U.S. government to enact the Digital Millennium Copyright Act of 1998. This law gives them total legal power over almost anything a reader might do with an e-book. Even reading it without authorization is a crime!

We still have the same old freedoms in using paper books. But if e-books replace printed books, that exception will do little good. With "electronic ink," which makes it possible to download new text onto an apparently printed piece of paper, even newspapers could become ephemeral. Imagine: no more used book stores; no more lending a book to your friend; no more borrowing one from the public library—no more "leaks" that might give someone a chance to read without paying. (And judging from the ads for Microsoft Reader, no more anonymous purchasing of books either.) This is the world publishers have in mind for us.

Why is there so little public debate about these momentous changes? Most citizens have not yet had occasion to come to grips with the political issues raised by this futuristic technology. Besides, the public has been taught that copyright exists to "protect" the copyright holders, with the implication that the public's interests do not count.

But when the public at large begins to use e-books, and discovers the regime that the publishers have prepared for them, they will begin to resist. Humanity will not accept this yoke forever.

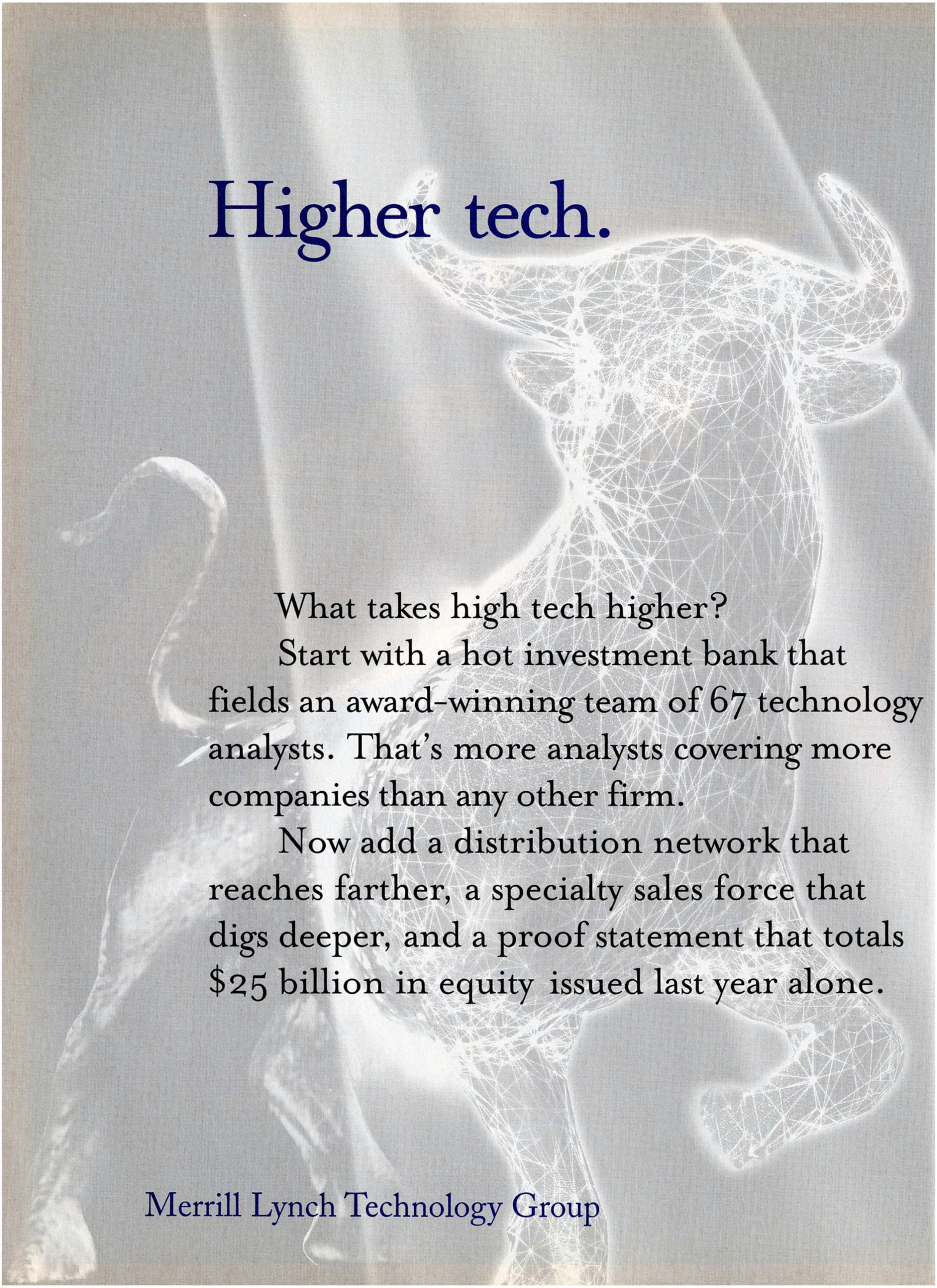
By legalizing the copying of e-books, we can turn copyright back into the industrial regulation it once was.

The publishers would have us believe that suppressive copyright is the only way to keep art alive, but we do not need a War on Copying to encourage a diversity of published works; as the Grateful Dead showed, private copying among fans is not necessarily a problem for artists. By legalizing the copying of e-books among friends, we can turn copyright back into the industrial regulation it once was.

For some kinds of writing, we should go even further. For scholarly papers and monographs, everyone should be encouraged to republish them verbatim online; this helps protect the scholarly record while making it more accessible. For textbooks and most reference works, publication of modified versions should be allowed as well, since that encourages improvement.

Eventually, when computer networks provide an easy way to send someone a small amount of money, the whole rationale for restricting verbatim copying will go away. If you like a book, and a box pops up on your computer saying "Click here to give the author one dollar," wouldn't you click? Copyright for books and music, as it applies to distributing verbatim unmodified copies, will be entirely obsolete. And not a moment too soon! ◊

Stallman is the founder of the GNU Project, the principal developer of the free software operating system GNU/Linux.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Silicon Handcuffs

IS BILL GATES WASHED UP?

Yes.

With these few words, I probably qualify for admission to an insane asylum. Surely, I must be joking. The world's richest man, a loser?

Yes, it's downhill from here for Gates, who turns 45 this year. His slide has nothing to do with age (or the prospects for Microsoft, his corporation, either). Instead, his is a cautionary tale of all innovators who strike it rich, gain renown, then seek to continue innovating.

Before I explain, let me remind you why Gates *is* an icon for innovators, not just capitalists. He is the greatest innovator of my lifetime, the first person in the computer industry to understand the importance of building a technological system—by hook or by crook. While other computer pioneers sneer that Gates copied this or that, they fail to see that the greatest innovations of all are those that mesh discrete inventions of others in order to launch society-wide transformations. Gates did that. Not Gary Kildall or Alan Kay or Tim Berners-Lee.

The only way for Bill Gates to escape the prison of success is to be willing to run the risk of looking foolish. Not easy.

So can Gates do it again? Can he do to the Web what he did for the desktop: create a durable standard that unlocked the value of thousands of inventions? Can Gates keep the fire?

Andy Grove, Intel's spiritual leader, has stressed the need to stay paranoid ("only the paranoid survive" is his credo). But being paranoid isn't enough to overcome the problem of how success corrupts American innovators.

We've all seen this with artists, but technologists pride themselves on the sort of hard-headedness that keeps the demons at bay. Yet this confidence is more myth than reality. Many innovators bask in the glory of their achievements, assuring that their innovative years are over. Howard Gardner, the Harvard psychologist, has shown convincingly that people who stay highly creative over a lifetime constantly gravitate toward the margins. Every time they gain acclaim, they move again to the margins—even at great cost to themselves financially and reputationally (for they may be ridiculed for abandoning a niche they dominate in order to strike out for unfamiliar territory).

To his credit, Gates *is* trying to move toward the margins. Giving up his role as chief executive officer at Microsoft suggests that he knows he must break the mold or stagnate. But in becoming Microsoft's software chief, he hasn't gone far enough afield. In fact, his new job—defining Microsoft's technical goals and deciding how best to package and present its innovations—sounds a lot like his old job.

The sad truth is that Gates can't free himself from the forces that are draining away his creativity. The world won't let him go to the margins. He's trapped in the silicon handcuffs of his own success. So he deserves sympathy. Not because he's lost his power, but because he's lost control of his life.

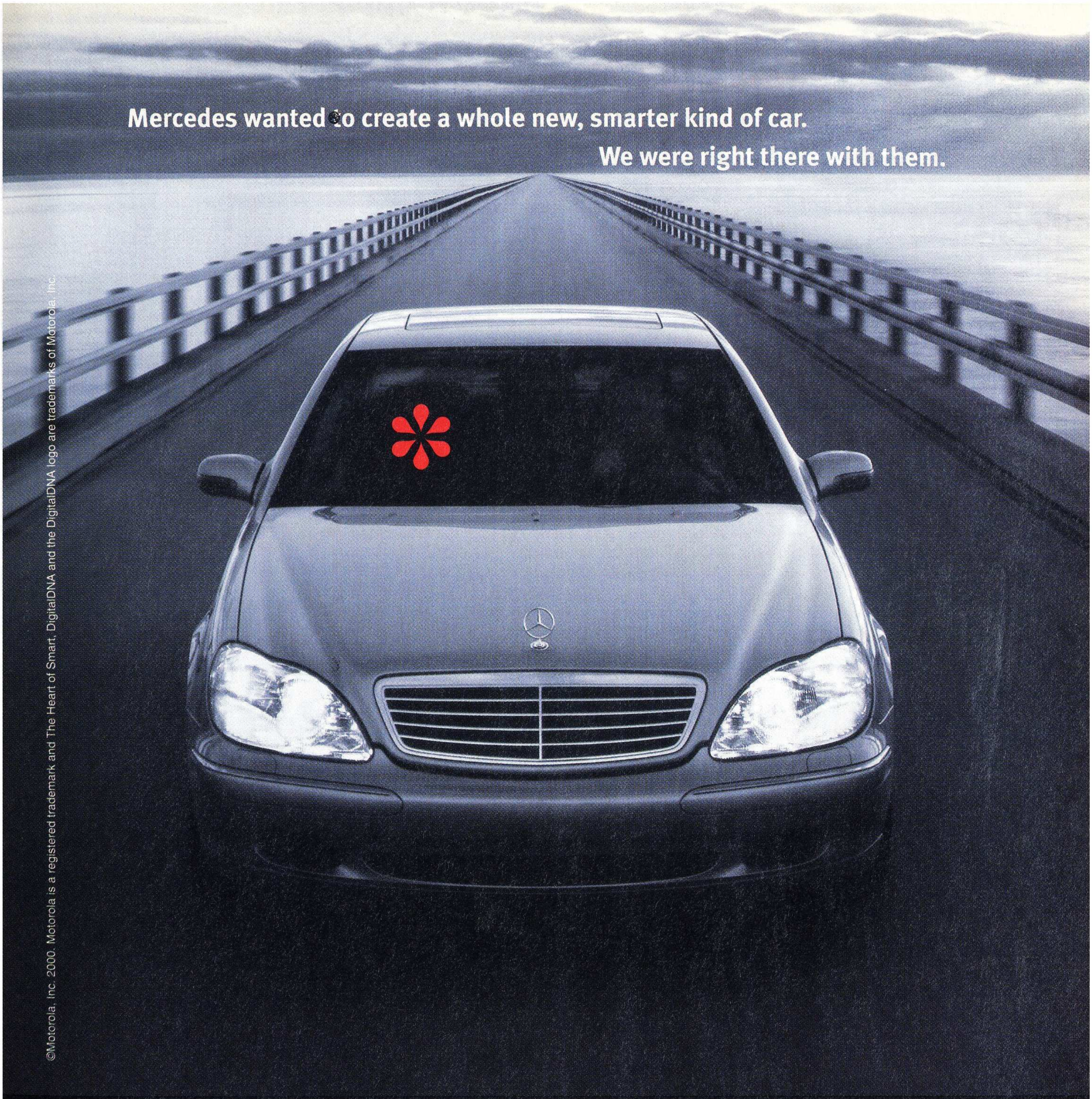
The demands on him just keep mounting. He is called upon to define the new frontiers of innovation. He also must notch big victories with his philanthropic foundation, now the world's richest. Gates recently admitted, "I'm doing a lot more philanthropy than I expected to at a young age." His early decisions seem uninspired: diseases in the developing world and university education for minority students. Worthy causes, but well-established (even moldy) ones, where Gates can't lead; he can only hand out big checks like the billion dollars he gave to the United Negro College Fund.

These gestures are meant to satisfy the public's desire to see Gates act like a philanthropist—while still limiting the insistent claims on his time that would result from being a fulltime foundation chief. But they are likely only to heighten the pressures on him to serve as an all-purpose savior. On a smaller scale, all successful innovators face this pressure in a world obsessed with the power and promise of technology. Not only must the innovator find the proper role for themselves in a company, or even an industry, spawned by their efforts. They must also work to defy society's image of them as the Newly Selfish.

Gates, of course, may somehow evade this trap. Like a cyber version of Picasso or Frank Sinatra, he may find ways to reinvent himself in his medium of choice. It is surely possible for even an icon to stay sharp. Look at Paul Allen, cofounder of Microsoft and Gates' childhood pal. Allen left Microsoft years ago and, while a super-billionaire himself, dodges the limelight. Perhaps for this reason he has shown a flair for quixotic projects: founding a museum for the late rock guitarist Jimi Hendrix; buying sports teams; peripatetic investing in the industries that spawn the digital age. His life lacks coherence, but it gives off brilliant sparks.

Allen reminds me of the time when I asked Gates if he would ever buy a jazz music label, a book publisher, a movie studio or in some other way indulge a private passion of his (this was six years ago, when I was regularly reporting on Microsoft). Gates looked at me blankly, then repeated his mantra that he would stay focused on software.

A sensible answer. But the wrong one if he wants to doff the handcuffs. Gates' unwillingness to pursue the frivolous and unexpected stands as a warning to all proven innovators. Only by making fools of themselves can they escape the prison of success. ◊



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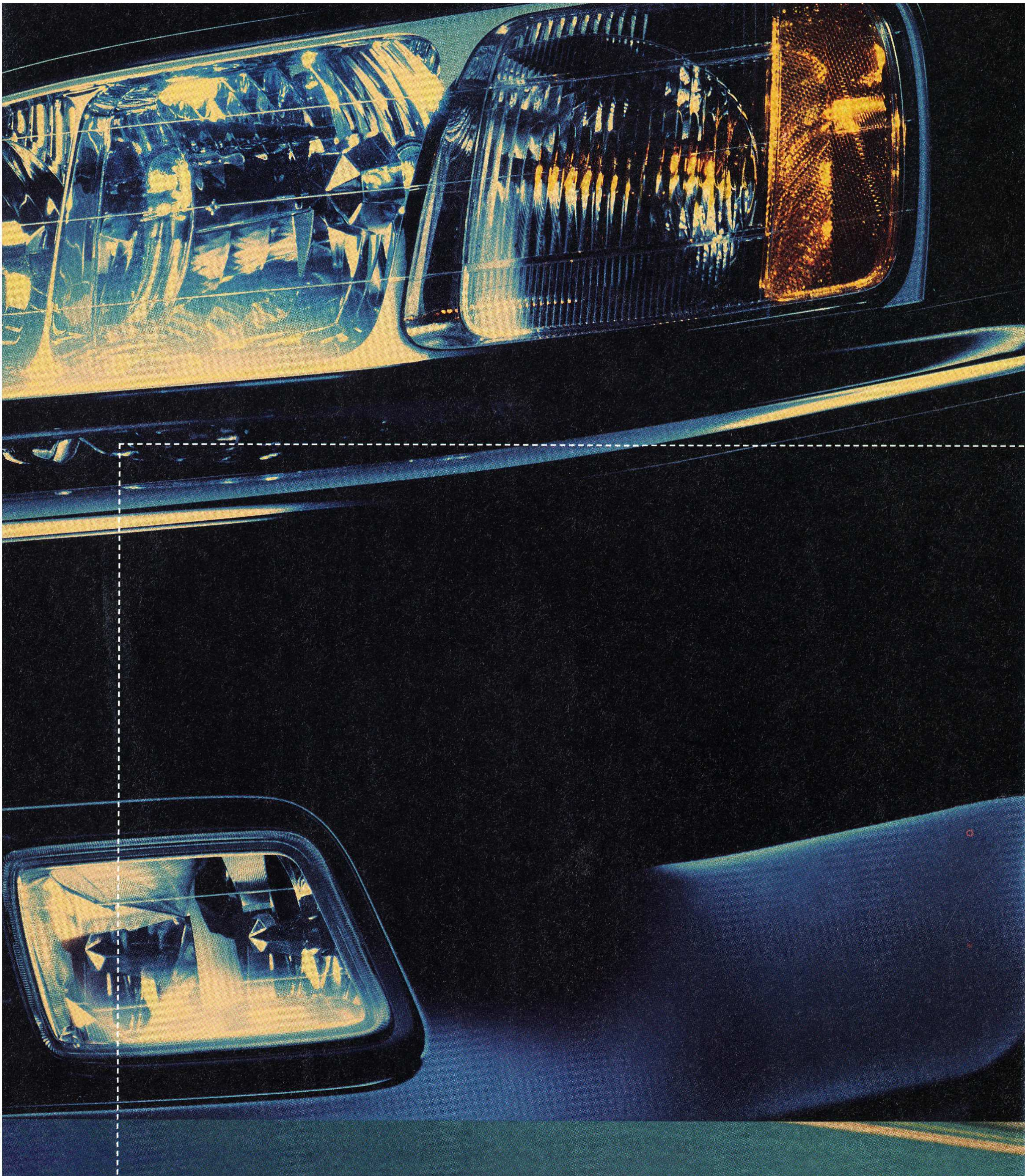

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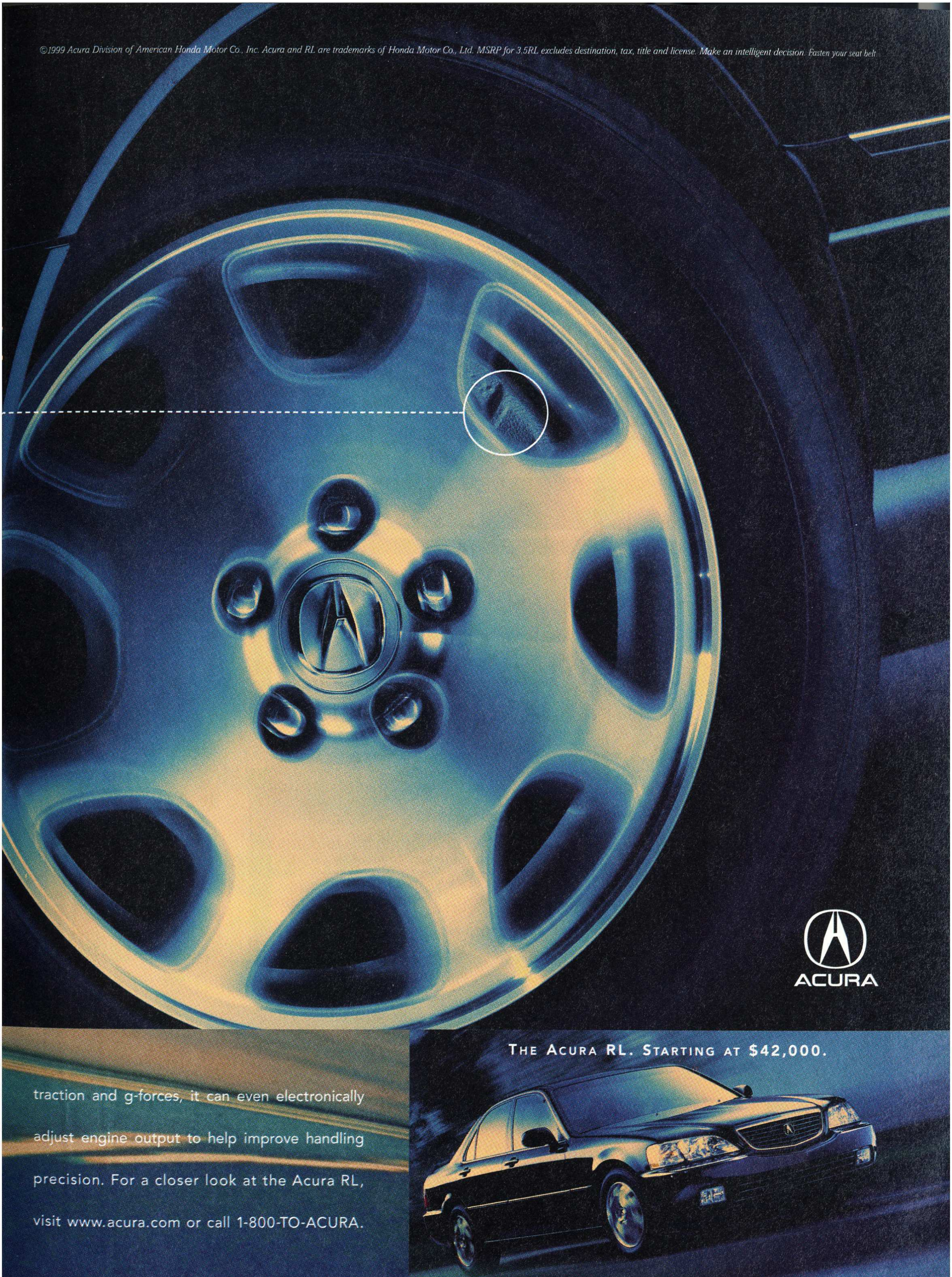

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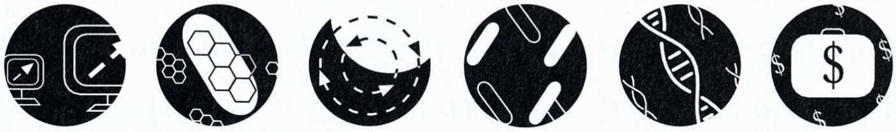


Beyond Silicon

The Future of Computing

MATTER STILL MATTERS. EVEN IN THE AGE OF VIRTUAL REALITY AND cyberspace, the underlying *stuff* of our technology is a big deal. Silicon, a grayish, common element that sits modestly between aluminum and phosphorus on the periodic table—glorified sand, really—has made possible the personal computer, the Internet, and the entire dot-com phenomenon. Like iron in 19th-century rails, silicon in 20th-century microchips has transformed society.

Silicon and computing are not inextricably linked, although from the vantage point of 2000, they often seem to be. In fact, computing can be done in a remarkable range of different kinds of stuff. The quantum properties of individual atoms can be used to store information. Organic molecules can be exploited as electronic switches. Even the constituents of our cells, including DNA, RNA and proteins, can be pressed into service as logic circuits. These are not daydreams. Each of these approaches is being explored as a possible successor to silicon. Turn the page, and enter the future of computing.

ICONS BY TERRY ALLEN • INFOGRAPHICS BY BETSY HAYES

The current economic boom is likely due to increases in computing speed and decreases in price. Now there are some good reasons to think that the party may be ending.

The End of Moore's Law?

BY CHARLES C. MANN

FROM TODAY'S PERSPECTIVE, IT SEEMS CLEAR THAT GORDON Moore got lucky. Back in 1965, Electronics magazine asked Moore—then research director of electronics pioneer Fairchild Semiconductor—to predict the future of the microchip industry. At the time, the industry was in its infancy; Intel, now the world's biggest chip-maker, would not be founded (by Moore, among others) for another three years. Because few chips had been manufactured and sold, Moore had little data to go on. Nonetheless, he confidently argued that engineers would be able to cram an ever-increasing number of electronic devices onto microchips. Indeed, he guessed that the number would roughly double every year—an exponential increase that has come to be known as Moore's Law.

At first, few paid attention to Moore's prediction. Moore himself admitted that he didn't place much stock in it—he had been "just trying to get across the idea [that] this was a technology that had a future." But events proved him right. In 1965, when Moore wrote his article, the world's most complex chip was right in his lab at Fairchild: It had 64 transistors. Intel's new-model Pentium III, introduced last October, contains 28 million transistors. "The sustained explosion of microchip complexity—doubling year after year, decade after decade," Lillian Hoddeson and Michael Riordan write in Crystal Fire, their history of the transistor, "has no convenient parallel or analogue in normal human experience."

PHOTOGRAPHS BY JANA LEŌN

The effect of Moore's Law on daily life is obvious. It is why today's $3,000 personal computer will cost $1,500 next year and be obsolete the year after. It is why the children who grew up playing Pong in game arcades have children who grow up playing Quake on the Internet. It is why the word-processing program that fit on two floppy disks a decade ago now fills up half a CD-ROM—in fact, it explains why floppy disks themselves have almost been replaced by CD-ROMs, CD-Rs and CD-RWs.

But these examples, as striking as they are, may understate the importance of Moore's Law. The United States is experiencing the longest economic boom since the 1850s, when the federal government first began collecting economic statistics systematically. The current blend of steady growth and low inflation is so unusually favorable that many economists believe the nation is undergoing fundamental change. And the single most important factor driving the change, these economists say, is the relentless rise in chip power. "What's sometimes called the 'Clinton economic boom,'" says Robert Gordon, an economist at Northwestern University, "is largely a reflection of Moore's Law." In fact, he says, "the recent acceleration in productivity is at least half due to the improvements in computer productivity."

If Gordon is right, it is unfortunate that just as economists are beginning to grasp the importance of Moore's Law, engineers are beginning to say that it is in danger of petering out.

In 1964, chips had as many as 32 transistors. By 1975, semiconductor chips were a thousand times more complex—just as Moore predicted.

THE AGE OF DIGITAL ELECTRONICS IS usually said to have begun in 1947, when a research team at Bell Laboratories designed the first transistor. But Moore's Law, the driving force of the digital era, is pegged to another, lesser-known landmark: the invention of the integrated circuit. John Bardeen, Walter Brattain and William Shockley won a Nobel Prize for the transistor. Jack Kilby, the Texas Instruments engineer who came up with the integrated circuit, didn't win anything. But in many ways it was his creation, not the transistor, that most shook the world.

In May 1958 Kilby was hired by Texas Instruments, the company that pioneered the silicon transistor. The company had a mass vacation policy; almost everyone was thrown out of the office for the first few weeks in July. Being newly hired, Kilby had no time off. He found himself almost alone in the deserted plant.

Transistors, diodes, capacitors and other now-familiar electronic devices had just been invented, but already some far-sighted people, many of them in the Pentagon, were thinking about lashing together these individual components into more complex circuits. Texas Instruments was trying to hook up with the Army's Micro-Module program, in which individual components were built on small wafers and stacked like so many poker chips. Kilby thought this approach was ludicrous—a kludge, in engineer's slang. By the time a module was large enough to do something interesting, the stack of wafers would be ridiculously big and cumbersome.

On July 24—exactly a month after Bell Labs celebrated the 10th anniversary of the public unveiling of the transistor—inspiration paid a visit to Kilby in the empty factory. Instead of wiring together components in modules, he wrote in his lab notebook, engineers should scatter "resistors, capacitors and transistors & diodes on a single slice of silicon." Classic inventors' stories usually include a chapter about how management ignores the inventor's brilliant new idea. At Texas Instruments, Kilby's boss immediately asked him to build a prototype. By September, Kilby had assembled one. It was simple and crude, but it worked. The company filed for a patent on its revolutionary "Solid Circuit" in February 1959.

Two weeks before the filing, a similar idea occurred to Robert Noyce, an engineer at Fairchild Semiconductor, one of the first startup tech firms in Silicon Valley. (Noyce and Moore would later leave Fairchild to found Intel.) Whereas Kilby had linked the components of his integrated circuit by gold wires and solder, Noyce realized the connections could be painted on the silicon with a kind of stencil—a photomicrolithograph, to be precise. Noyce's bosses, like Kilby's, were enthusiastic. And in July Fairchild, too, filed for a patent.

Litigation inevitably ensued. It lasted 10 years and ended with the companies fighting to a draw. But while the lawyers argued, both companies raced to create ever-more-sophisticated integrated circuits—"chips," as they came to be called. The first chip appeared on the market in 1961, to less than universal acclaim; engineers, accustomed to designing their own circuits, initially regarded these prefabricated gizmos as annoyances. But the companies kept going. By 1964 some chips had as many as 32 transistors; when Moore wrote his article in 1965, a chip in his R&D lab had twice as many.

One component (1959), 32 (1964), 64 (1965)—Moore put these numbers on a graph and connected the dots with a line. "The complexity [of cheap integrated circuits] has increased at a rate of roughly a factor of two per year," he wrote. Then he got out a ruler and extended the line into the future. It sailed off the top of his graph and into the stratosphere. "Over the longer term...," Moore argued, "there is no reason to believe [the rate of increase] will not remain constant for at least 10 years." In other words, the companies that were then laboring to create microchips with 64 components would in a decade be manufacturing microchips with over 65,000 components—a jump of more than three orders of magnitude.

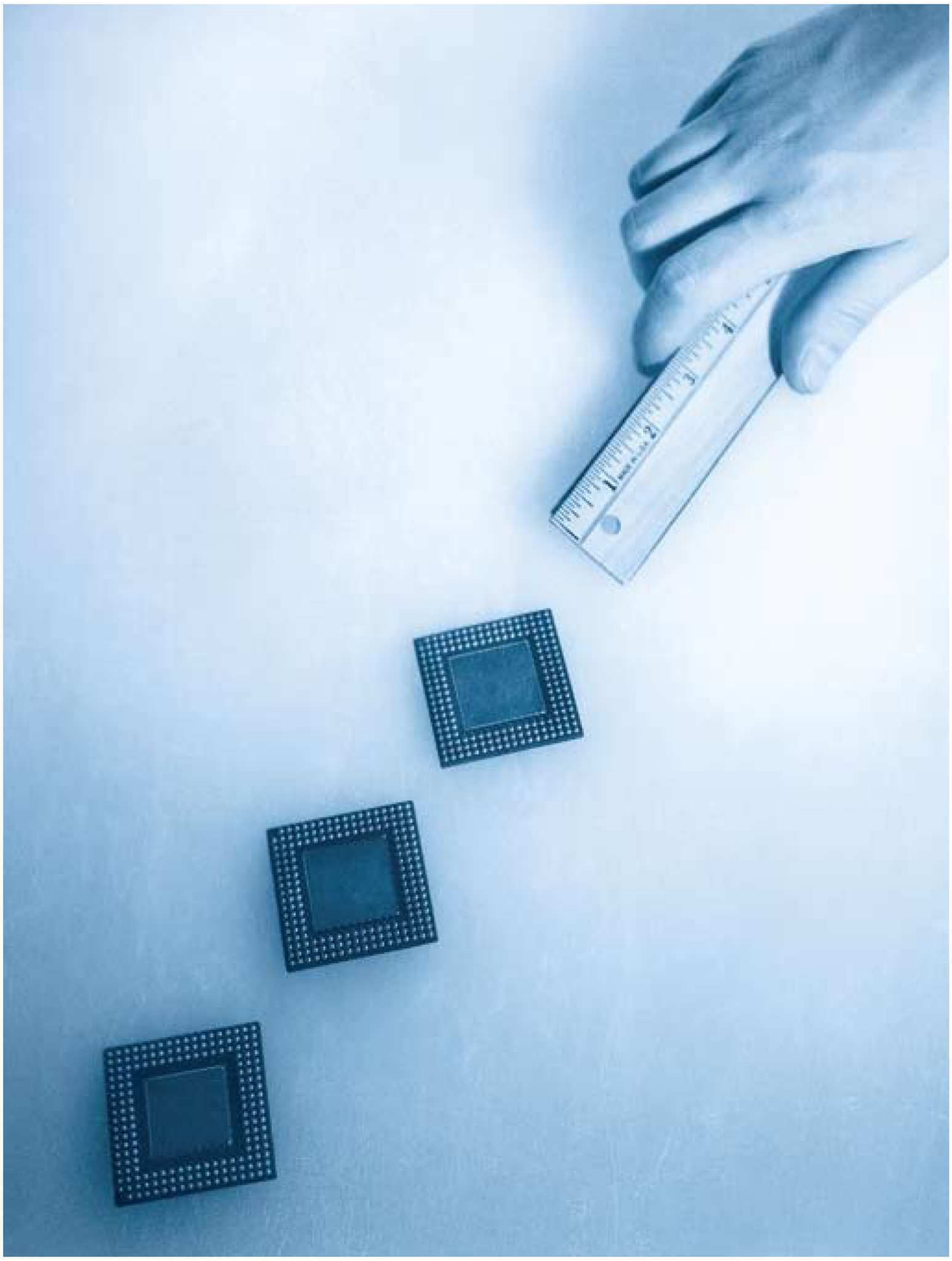
Moore's Law was not, of course, a law of nature. It was more like an engineer's rule of thumb, capturing the pattern Moore had discerned in the early data on microchip production. But law or no, by 1975 engineers were designing and manufacturing chips a thousand times more complex than had been possible just 10 years before—just as Moore had predicted. That year, Moore revisited his prediction at the annual International Electron Devices Meeting of the Institute of Electrical and Electronics Engineers, the professional association of electrical engineers. Acknowledging the increasing difficulty of the chip-making process, Moore slightly revised his "law." From that point on, he said, the number of devices on a chip would double every

two years. This prediction proved correct, too. Today, some people split the difference and say that microchip complexity will double every 18 months; other people loosely apply the term "Moore's Law" to any rapidly improving aspect of computing, such as memory storage or bandwidth.

Despite the fuzziness about exactly what Moore's Law states, its gist is indisputable: Computer prices have fallen even as computer capabilities have risen. At first glance, this is unsurprising. Although digital gurus often herald the advent of better products at lower costs as an unprecedented boon, it is in fact an economic commonplace. A car from 1906, which by today's standards is barely functional, then cost the equivalent of $52,640, according to a study by Daniel Raff of the Wharton School of Business and Manuel Trajtenberg of Tel Aviv University. Nonetheless, the digital gurus have a point. The improvements in computer chips have been unprecedentedly rapid—"manna from heaven," in the phrase of Erik Brynjolfson, an economist at MIT's Sloan School of Management. "It's this lucky combination of geometry and physics and engineering," he says. "The technical innovation is normal, but the rate at which it is occurring is highly unusual."

Drawn by rapidly improving products at rapidly falling prices, U.S. spending on computers has risen for the last twenty years at an average annual clip of 24 percent—a Moore's Law of its own. In 1999, U.S. companies spent $220 billion on computer hardware and peripherals, more than they invested in factories, vehicles or any other kind of durable equipment. Computers became so ubiquitous and powerful that it became commonplace to hear the claim that the nation was in the middle of a "digital revolution." Moore's Law, the pundits claim, has created a "new economy."

Maybe so, but for a number of years the evidence didn't seem to be there. Like everyone else, economists had been discovering the wonders of the inexpensive beige boxes now on their desks. They kept waiting to see the rewards of computing pop up in the government statistics on income, profits and productivity. But it didn't happen. Throughout the 1980s and the first part of the 1990s the huge national investment in digital technology seemed to have almost no payoff; Moore's Law ended up boosting profits for chip-makers, but hardly anyone else. "We see the computer age everywhere except in the productivity statistics," the Nobel Prize-winning MIT economist Robert M. Solow remarked in 1987.



The puzzle—huge expenditures with little apparent benefit—became known as the "productivity paradox." Not only were these new technical wonders not useful, some researchers argued, they might actually be harmful. Since 1980 the service industries alone have spent more than a trillion dollars on computer hardware and software. Yet Stephen S. Roach, chief economist of Morgan Stanley, suggested in 1991 that this had merely transformed the service sector from an industry characterized by variable labor costs to one that was increasingly dominated by fixed hardware costs. The least productive "portion of the economy," Roach argued, "[is] the most heavily endowed with high-tech capital"—the more computers, in other words, the less value.

"Look at hotel checkouts," says Lester Thurow, one of Brynjolfson's colleagues at Sloan. "They're completely computerized now, but nobody seems to be doing anything faster. The same thing at the supermarket—you wait in line just as long as you used to wait." To Thurow, the service sector, which is almost three-quarters of the economy, "seems at first glance to have swallowed vast amounts of computing power without a trace."

"Nobody could understand it," says Hal Varian, an economist at the School of Information Management Systems at the University of California, Berkeley ("What Are the Rules, Anyway?" TR March/April 1999). "On the face of it, the statistics coming out of the government were saying that

this massive investment was senseless. In the past, technological innovation has almost invariably increased living standards—look at electricity, railroads, telephones, antibiotics. And here was Moore's Law—innovation of unprecedented rapidity—that seemed to create nothing for human welfare. But if computers had so little payoff, why was everyone rushing to buy the damned things?"

To people like Varian, what happened at the Federal Trade Commission is an example of what should have been going on all over the country. In the mid-1980s, the FTC gave a personal computer to every staffer in the Bureau of Economics, its in-house economic advisory board. "The computers had two effects," recalls a former FTC economist. "For the first three months, the economists spent long hours worrying about their fonts"—that is, about making their letters and memos look pretty. "Six months later, they got rid of the steno pool."

For economists, this is a textbook example of increased productivity. The agency produced the same number of reports with fewer people, which means the per-capita production of economics was higher. (More precisely, this is an example of increased labor productivity; economists also use another, more complex measure, multifactor productivity, but for most purposes the two can be treated together.)

Spread throughout the economy, higher productivity means higher wages, higher profits, lower prices. Productivity increases aren't necessarily painless, as the dismissed stenographers at the FTC found out. But history shows that workers displaced by productivity-enhancing technology usually find other, better jobs. In the long run raising productivity is essential to increasing the national standard of living. "In some sense," Thurow says, "if you could only know one number about an economy, you'd like to know the level and the rate of growth of productivity, because it underlies everything else."

After World War II, the United States spent decades with productivity growing at an average rate of almost 3 percent a year—enough, roughly speaking, to double living standards every generation. In 1973, however, productivity growth suddenly slowed to 1.1 percent, far below its previous level. Nobody knows why. "The post-1973 productivity slowdown," says Jack Triplett of the Brookings Institute, "is a puzzle that has so far resisted all attempts at solution."

The effects of the slowdown, alas, are well-known. At that slower rate, living standards double in three generations, not one. The result was stagnation. Wage-earners still won raises, but employers, unable to absorb the extra costs with higher productivity, simply passed the increase into higher prices, which canceled the benefit of higher wages. Unsurprisingly, economists say, the unproductive 1970s and 1980s were years of inflation, recession, unemployment, social conflict and enormous budget deficits.

In 1995, productivity changed direction again. Without any fanfare, it abruptly began rising at an annual average clip of almost 2.2 percent—a great improvement from the 1980s, though still less than the 1960s. At first, most researchers regarded the increase as a temporary blip. But gradually many became convinced that it was long-lasting. "It was certainly something we discussed a lot at [Federal Reserve Board] meetings," says Alice Rivlin, a Brookings economist who recently left the board. "You know, 'Is this increase real?' By now, I think most economists believe it is." The implications, in her view, are enormous: Renewed productivity growth means that more people are more likely to achieve their dreams.

Although Rivlin is co-leading a Brookings study to determine the cause of the new productivity boom, she and many other economists believe it is probably due to computerization. "Moore's Law," she says, laughing, "may finally be paying off."

There are two reasons for this belief, says Alan S. Blinder, a Princeton University economist. First, the acceleration in productivity happened "co-terminously" with a sudden, additional drop in computer costs. Second, the coincidence that productivity rose just as business adopted the Internet "is just too great to ignore."

In the mid-'90s, Blinder says, "the rate of computer deflation moved from minus 10 percent to minus 25 percent per annum. And although the computer industry is a small fraction of GNP—less than 2 percent—the drop in costs has been so severe that as a matter of arithmetic it knocks a noticeable piece off the overall price index." In fact, the recent declines in the price of computers are so big that Gordon, the economist at Northwestern, argues that they largely explain the bump in productivity—except for durable goods manufacturing the economy is stagnant.

Gordon's argument is "too extreme," in the view of Chris Varvares, president of Macroeconomic Advisers, an economic modeling firm in St. Louis. "Why would business invest in all this equipment if they didn't have the expectation of a return? And since it's gone on for so long, why wouldn't they have the reality?" Instead, he says, computers and the Internet are finally paying off in ways that statistics can measure. When banks introduce automated teller machines, the benefits don't show up in government statistics. Bank customers are better off, because they can withdraw and deposit money at any time and in many more places. But the bank itself is still doing what it did before. "The benefits are captured by consumers, and don't show up in the bottom line as output," says Varvares. Only recently, he argues, did computers hit a kind of critical mass; workers had so much digital power on their desks that it muscled its way into the statistics.

Not every economist agrees. "You'd like to be able to tell yourself a story about how something could be true," Thurow says. "In this case, are we saying that people suddenly figured out how to use computers in 1996?" No, other economists say, but businesses do need time to accommodate new technologies. Electricity took more than two decades to exert an impact on productivity, according to Stanford University economic historian Paul A. David. Computers simply encountered the same lag. But by now, Brynjolfson says, "computers are the most important single technology for improving living standards. As long as

Without any fanfare, in 1995 productivity abruptly began rising again. Many economists now believe it's probably due to computerization.

Moore's Law continues, we should keep getting better off. It will make our children's lives better."

The explosion in computer power has become so important to the future, these economists say, that everyone should be worried by the recent reports that Moore's Law might come to a crashing halt.

THE END OF MOORE'S LAW HAS BEEN predicted so many times that rumors of its demise have become an industry joke. The current alarms, though, may be different. Squeezing more and more devices onto a chip means fabricating features that are smaller and smaller. The industry's newest chips have "pitches" as small as 180 nanometers (billionths of a meter). To accommodate Moore's Law, according to the biennial "road map" prepared last year for the Semiconductor Industry Association, the pitches need to shrink to 150 nanometers by 2001 and to 100 nanometers by 2005. Alas, the road map admitted, to get there the industry will have to beat fundamental problems to which there are "no known solutions." If solutions are not discovered quickly, Paul A. Packan, a respected researcher at Intel, argued last September in the journal Science, Moore's Law will "be in serious danger."

Packan identified three main challenges. The first involved the use of "dopants," impurities that are mixed into silicon to increase its ability to hold areas of localized electric charge. Although transistors can shrink in size, the smaller devices still need to maintain the same charge. To do that, the silicon has to have a higher concentration of dopant atoms. Unfortunately, above a certain limit the dopant atoms begin to clump together, forming clusters that are not electrically active. "You can't increase the concentration of dopant," Packan says, "because all the extras just go into the clusters." Today's chips, in his view, are very close to the maximum.

Second, the "gates" that control the flow of electrons in chips have become so small that they are prey to odd, undesirable quantum effects. Physicists have known since the 1920s that electrons can "tunnel" through extremely small barriers, magically popping up on the other side. Chip gates are now smaller than two nanometers—small enough to let electrons tunnel through them even when they are shut. Because gates are supposed to block electrons, quantum mechanics could render smaller silicon devices useless. As Packan says, "Quantum mechanics isn't like an ordinary manufacturing difficulty—we're running into a roadblock at the most fundamental level."

Semiconductor manufacturers are also running afoul of basic statistics. Chipmakers mix small amounts of dopant into silicon in a manner analogous to the way paint-makers mix a few drops of beige into white paint to create a creamy off-white. When homeowners paint walls, the color seems even. But if they could examine a tiny patch of the wall, they would see slight variations in color caused by statistical fluctuations in the concentration of beige pigment. When microchip components were bigger, the similar fluctuations in the concentration of dopant had little effect. But now transistors are so small they can end up in dopant-rich or dopant-poor areas, affecting their behavior. Here, too, Packan says, engineers have "no known solutions."

Ultimately, Packan believes, engineering and processing solutions can be found to save the day. But Moore's Law will still have to face what may be its most daunting challenge—Moore's Second Law. In 1995, Moore reviewed microchip progress at a conference of the International Society for Optical Engineering. Although he, like Packan, saw "increasingly difficult" technical roadblocks to staying on the path predicted by his law, he was most worried about something else: the increasing cost of manufacturing chips.

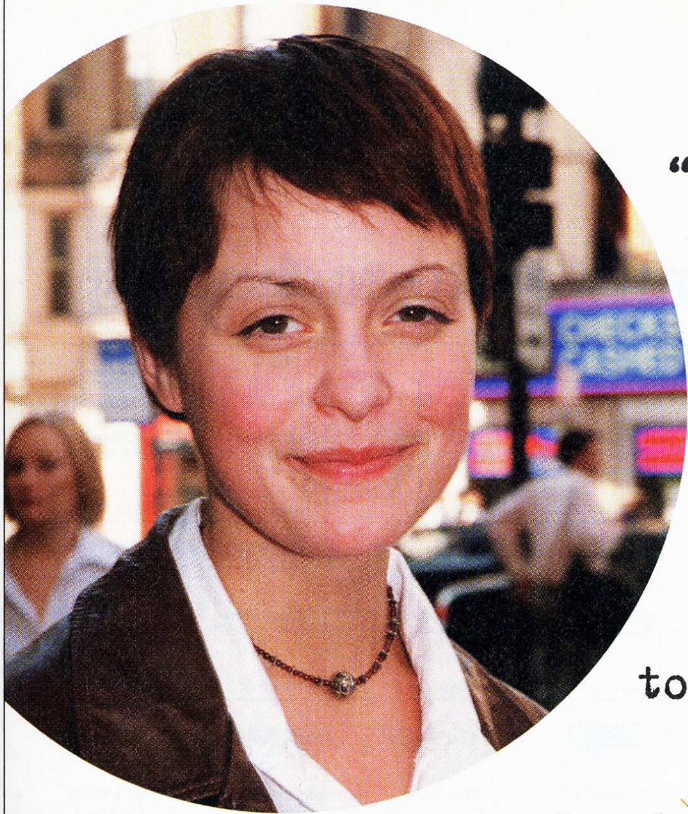
When Intel was founded in 1968, Moore recalled, the necessary equipment cost roughly $12,000. Today it is about $12 million—but it still "tends not to process any more wafers per hour than [it] did in 1968." To produce chips, Intel must now spend billions of dollars on building each of its manufacturing facilities, and the expense will keep going up as chips continue to get more complex. "Capital costs are rising far faster than revenue," Moore noted. In his opinion, "the rate of technological progress is going to be controlled [by] financial realities." Some technical innovations, that is, may not be economically feasible, no matter how desirable they are.

Promptly dubbed "Moore's Second Law," this recognition would be painfully familiar to anyone associated with supersonic planes, mag-lev trains, high-speed mass transit, large-scale particle accelerators and the host of other technological marvels that were strangled by high costs. If applied to Moore's Law, the prospect is dismaying. In the last 100 years, engineers and scientists have repeatedly shown how human ingenuity can make an end run around the difficulties posed by the laws of nature. But they have been much less successful in cheating the laws of economics. (The impossible is easy; it's the unfeasible that poses the problem.) If Moore's Law becomes too expensive to sustain, Moore said, no easy remedy is in sight.

> The imminent demise of Moore's Law has been predicted before. This time, the industry is facing **roadblocks** at the most fundamental level.

Actually, that's not all that he said. Moore also argued that the only industry "remotely comparable" in its rate of growth to the microchip industry is the printing industry. Individual characters once were carved painstakingly out of stone; now they're whooshed out by the billions at next to no cost. Printing, Moore pointed out, utterly transformed society, creating and solving problems in arenas that Gutenberg could never have imagined. Driven by Moore's Law, he suggested, information technology may have an equally enormous impact. If that were the case, the ultimate solution to the limits of Moore's Law may come from the very explosion of computer power predicted by Moore's Law itself—"from the swirl of new knowledge, methods and processes created by computers of this and future generations."

The idea sounds far-fetched. But then Moore's Law itself sounded far-fetched in 1965. ◊



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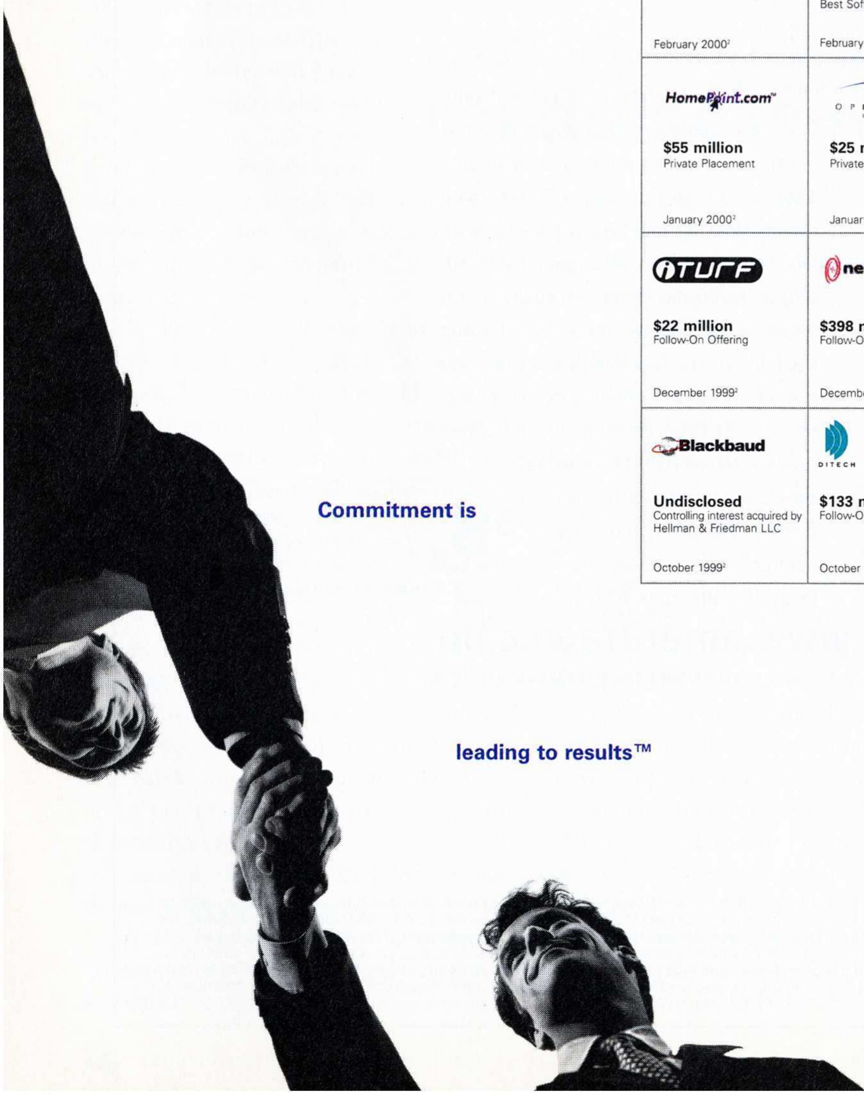
Blackbaud **Undisclosed** Controlling interest acquired by Hellman & Friedman LLC October 1999[2]	DITECH **$133 million** Follow-On Offering October 1999[2]	DSL.net **$62 million** Initial Public Offering October 1999[2]	women.com **$43 million** Initial Public Offering October 1999[2]	Bluestone Software **$69 million** Initial Public Offering September 1999[2]



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National Discount Brokers | ndb.com **$99 million** Follow-On Offering June 1999[2]	uniphase **$3.3 billion** Has merged with JDS FITEL Inc. June 1999[2]	flycast **$80 million** Initial Public Offering May 1999[1]	NETObjects **$72 million** Initial Public Offering May 1999[1]	Private Business **$40 million** Initial Public Offering May 1999[1]	iTurf **$106 million** Initial Public Offering April 1999[1]	PROXICOM **$67 million** Initial Public Offering April 1999[1]
sage **$130 million** Has acquired Tetra plc April 1999[4]	SoftNet Systems, Inc. **$152 million** Follow-On Offering April 1999[1]	asc Automated Securities Clearance Ltd. **$286 million** Has been acquired by SunGard Data Systems Inc. March 1999[1]	autobytel.com **$112 million** Initial Public Offering March 1999[1]	CDNOW **$264 million** Merger with N2K Inc. March 1999[1]	killer app **$49 million** Has been acquired by CNET, Inc. March 1999[1]	OneMain.com your hometown internet **$215 million** Initial Public Offering March 1999[1]
POWERWAVE TECHNOLOGIES **$62 million** Follow-On Offering March 1999[1]	sage **$145 million** Has acquired Peachtree Software, Inc. February 1999[4]	Hiway Technologies **$288 million** Has been acquired by Verio Inc. January 1999[1]	MarketWatch.com **$54 million** Initial Public Offering January 1999[1]	Smith-Gardner **$61 million** Initial Public Offering January 1999[1]	TERAYON **$142 million** Follow-On Offering January 1999[1]	womencom **Undisclosed** Merger with Hearst's HomeArts.com January 1999[1]

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Imagine computers orders of magnitude more powerful and far cheaper than today's machines. That's one promise of a field that uses individual molecules as microscopic switches.

BY DAVID ROTMAN

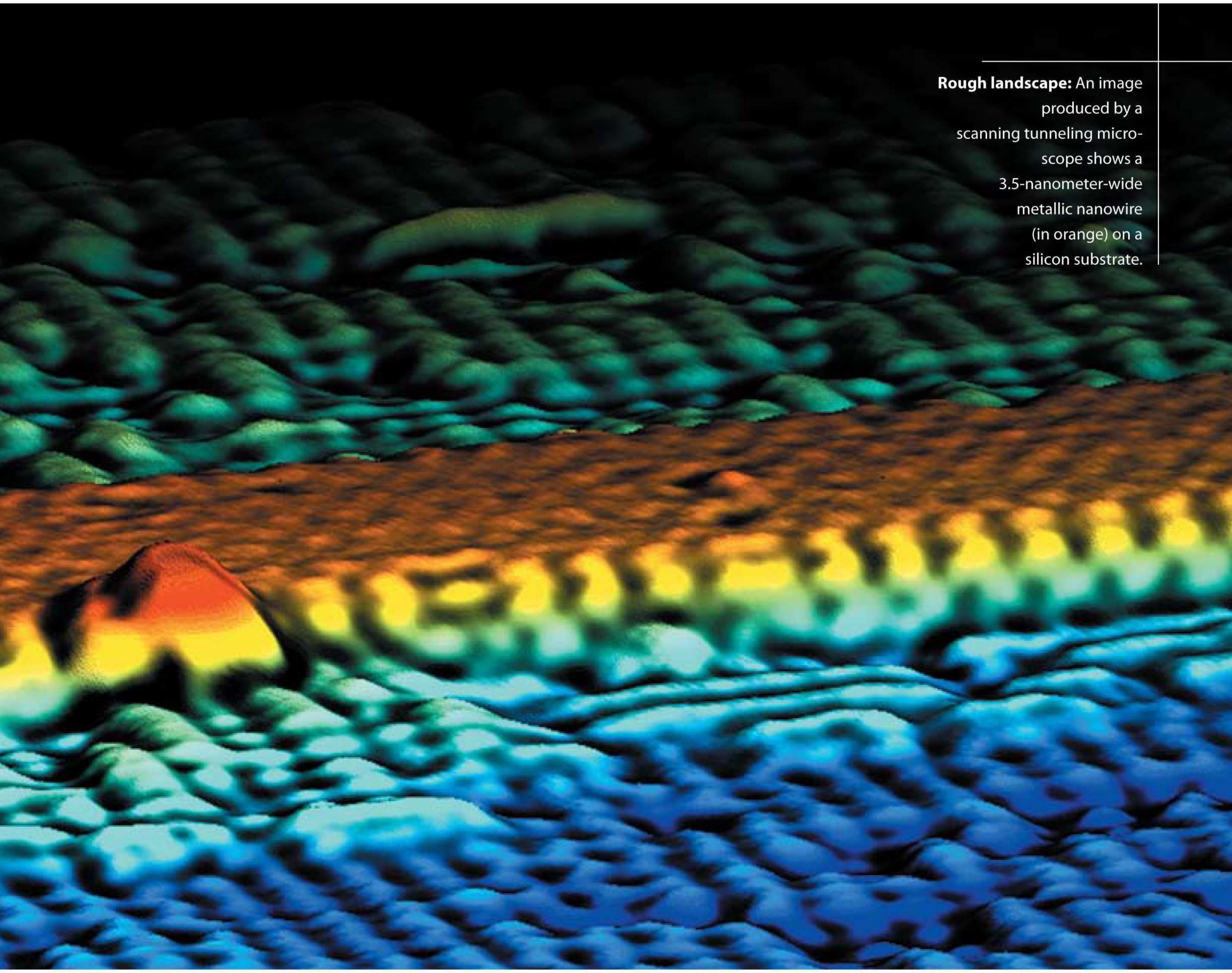
Molecular Computing

FOR MARK REED, THE FUTURE OF MOLECULAR ELECTRONICS HAS just arrived. A self-described "device guy," Reed, who heads Yale University's electrical engineering department, prides himself on having a distinctly practical bent. Ask him about the possibility of one day using molecules to replace silicon in computers that are billions of times faster than today's PCs or that fit on the head of a pin, and he grimaces. "I don't know how to do that. I don't think anyone does," he says dismissively.

But that doesn't dim the excitement that Reed, a leading researcher in molecular electronics, is feeling. Using molecules synthesized by Rice University chemist James Tour, Reed has fabricated electronic memories and a simple logic element made up of molecules that function as tiny, individual switches. The devices, which rely on small organic molecules tailored by the Rice chemists to have just the right electronic properties, are crude laboratory experiments. But they work—the molecules acting as a component in ultrasmall electronic devices able to turn current "on" and "off." What's more, these early prototypes have already shown hints of performing memory and logic tricks not possible with silicon semiconductors.

Most impressive, says Reed, is that the molecular devices are astonishingly easy—and potentially cheap—to make. You simply dip a silicon wafer lined with metal electrodes into a beaker filled with the right chemicals and give the molecules a few minutes to form on the electrodes. If you're clever enough with the chemistry, it's possible to coax the molecules to spontaneously orient themselves on the electrodes. "It works beautifully—and it works every time," says Reed.

It may work every time, but there's considerable controversy about what these chemical reactions will ever amount to. While true believers envision a world in which microscopic molecular computers made at low cost perform remarkable calculations, skeptics think the field has lost sight of the real world of engineering lim-



Rough landscape: An image produced by a scanning tunneling microscope shows a 3.5-nanometer-wide metallic nanowire (in orange) on a silicon substrate.

HEWLETT-PACKARD

its. Meanwhile, "device guys" like Reed think the future—in the form of workable prototypes that can be integrated with conventional silicon technology—is now.

The core advantage of molecular computing is the potential to pack vastly more circuitry onto a microchip than silicon will ever be capable of—and to do it cheaply. Semiconductor-makers can now cram about 28 million transistors on a chip by shrinking the smallest features of the transistors down to about 180 nanometers (billionths of a meter). Using conventional chip-making methods, however, the smaller you make a feature, the more expensive and difficult the process becomes. Many semiconductor experts doubt commercial fabrication methods can economically make silicon transistors much smaller than 100 nanometers. And even if chipmakers could figure out a reasonable way to etch them onto a chip, ultrasmall silicon components probably wouldn't work: At transistor dimensions of around 50 nanometers, the electrons begin to obey odd quantum laws, wandering where they're not supposed to be.

Molecules, on the other hand, are only a few nanometers in size, making possible chips containing billions—even trillions—of switches and components. In initial experiments, scientists have sandwiched a large number of molecules between metal electrodes. The devices work, however, because each molecule operates as a switch. If it were possible to wire a small number of molecules together as individual electronic components to form circuits, the result would change everything in computer design. Molecular memories could have a million times the storage density of today's best semiconductor chips, making it possible to store the experiences of a lifetime in a gadget the size of a wristwatch. Supercomputers could be small enough and cheap enough to incorporate into clothing. Worries that computing technology will soon hit a wall *(see "The End of Moore's Law?" p. 42)* would disappear.

Those applications are decades off—if they ever materialize. Still, Reed argues, some uses for molecular electronics could soon be feasible. Ultrasmall, cheap molecular devices could sit side-by-side with silicon, reducing the number of transistors and the power required by the circuit. "This is something you could use *today,* something you could sell in Radio Shack," says Reed. "This has a chance to totally change the economics of silicon."

To make that a reality, Reed, Tour and chemists from Pennsylvania State University have co-founded a startup called Molecular Electronics. The group declines to say what the initial products will be, but Tour says having "a working system in a couple years doesn't seem unrealistic."

Until very recently, that prediction would have seemed far-fetched. But in the

last year, the field has taken a leap from theory to the realm of the practical. Like their competitors at Yale and Rice, a West Coast collaboration of chemists and computer scientists from Hewlett-Packard and the University of California, Los Angeles, have recently characterized molecules capable of acting as electronic switches and memory *(see "Computing After Silicon,"* TR *September/October 1999).* R. Stanley Williams, who heads the effort at HP, says his team expects to build a prototype of a logic circuit that integrates a small number of nanoscale molecular devices within 18 months. "We have the switches and wires—the components to actually make true nanocircuitry," says Williams.

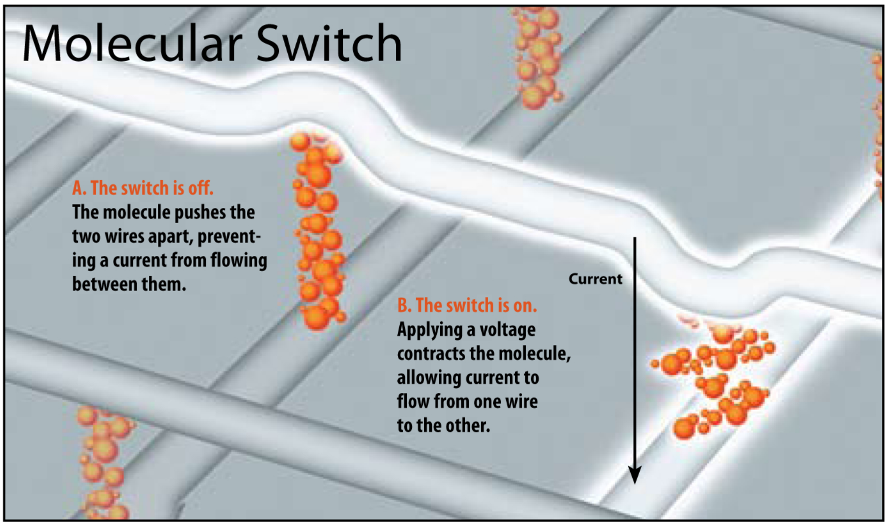
Being able to wire a small number of molecules together as **individual** electronic components would change everything in computer design.

The Recipe

IN THEORY, AT LEAST, ASSEMBLING A molecular electronic device is straightforward. In the version of the recipe favored by the HP/UCLA collaboration, the scientists first make a single monolayer of the right organic molecules in a chemical apparatus called a Langmuir trough; they then dip a silicon substrate covered by a pattern of metal electrodes into the trough. If the chemistry is just right, the molecules will bind to the metal electrodes, neatly orienting themselves. A second set of electrodes is then deposited on the molecules; the result is a monolayer of the organic molecules sandwiched between metal electrodes.

The challenge is that most organic molecules are not electrical conductors at all—never mind having the electronic properties that let them work as an effective switch. What is needed to make the system function electronically are specially tailored molecules that turn on and off repeatedly in a reliable and detectable way (the properties that have made silicon so successful). Coming up with molecules able to do the trick is the domain of chemistry wizards like Rice's Tour and UCLA's James Heath and Fraser Stoddart.

Their wizardry began paying off in a big way last fall. First, the HP/UCLA group published a paper describing what is in effect a molecular fuse—a one-time switch based on a complex, dumbbell-shaped organic molecule called rotaxane; the scientists have subsequently made reversible switches. They also showed how the device could perform simple logic and memory functions. Within months the Yale/Rice collaboration rivaled that feat by describing the synthesis of other organic molecules that act as electronic devices.



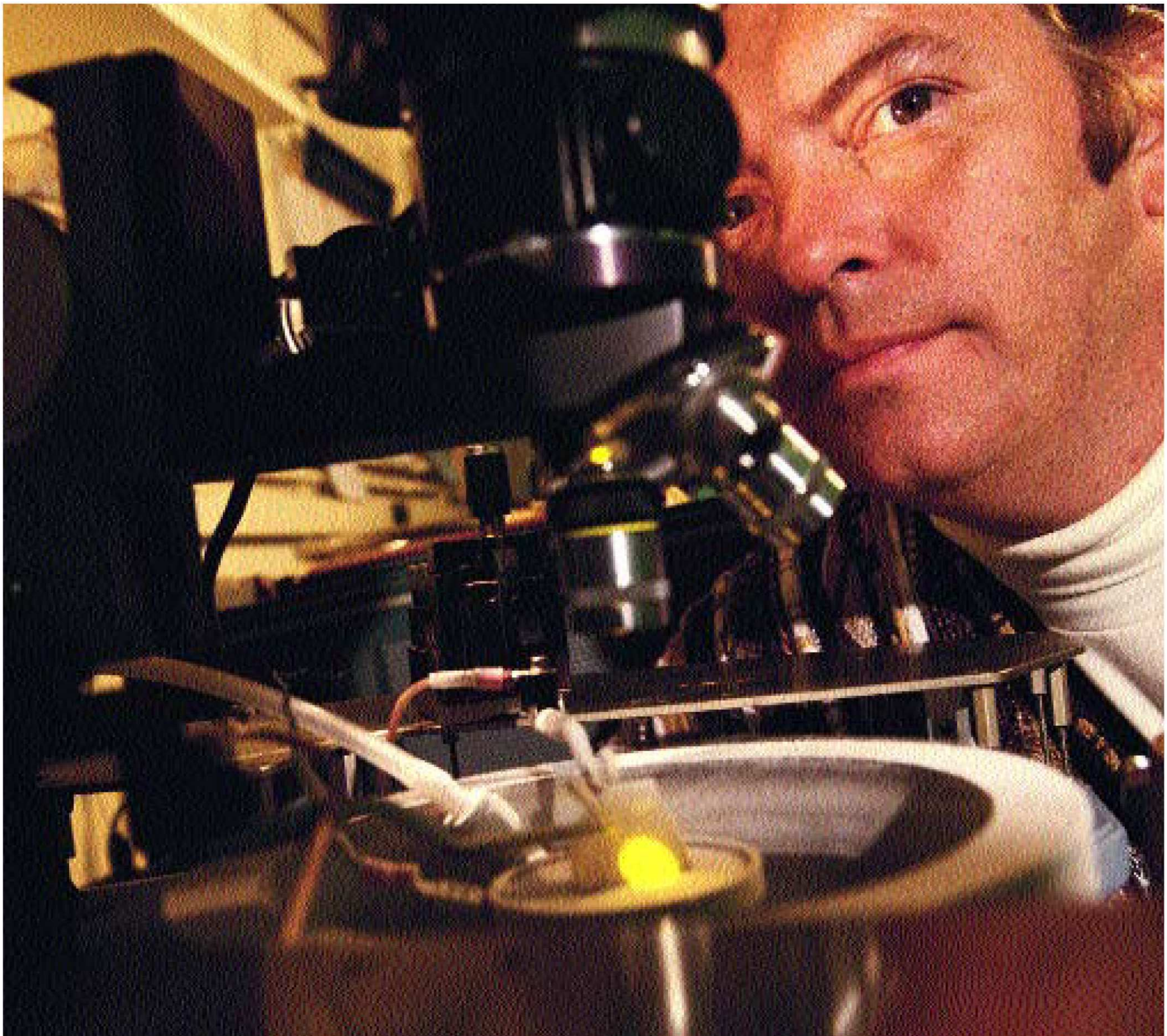
BETSY HAYES; SOURCE: HEWLETT-PACKARD

In a device envisioned by the HP/UCLA scientists, molecules would act as a simple switch, turning the current between two wires on and off. In one proposed mechanism, fully extended molecules push the wires apart (A), diminishing the electronic "tunneling" between the wires. Application of a relatively large voltage across the wires makes the molecule contract (B), closing the gap and enhancing tunneling. Because the tunneling rate depends exponentially on the width of the gap, a small change in the gap produces a dramatic variation in current flow. To determine the state of the switch, a much smaller voltage is applied and used to measure the resistance of the junction. Experiments to date have used broad wires and millions of molecules at each junction, but a nanowire prototype using a far smaller number of molecules is in the works.

Despite the differences in molecular particulars, the two research groups are taking advantage of the same quantum effects that could eventually set fundamental limits on silicon semiconductors. The molecules separating the two electrodes would normally block the flow of current. In the nanoworld of individual molecules, however, electrons can "tunnel" through a barrier that, according to classical physics, should block their path. By manipulating a voltage placed across the electrodes, the scientists can adjust the tunneling rate and thus turn the current on or off *(see illustration, left).*

Reed has already started thinking of ways to use molecular devices in combination with conventional silicon. One type of quantum logic gate that Reed has recently built would, for example, do the same specialized function as seven much larger silicon transistors, significantly reducing the size and power consumption of an integrated circuit. And while fabricating conventional transistors requires complex and expensive processing, the molecular device can be "glued on" to the circuit, says Reed.

Molecules could also provide ultracheap electronic memory with some attractive properties. The most common type of semiconductor memory is called DRAM, for dynamic random access memory. (This is the short-term memory your computer relies on when it's running a program.) The problem with DRAM is that the stored information evaporates when the power is shut off—it's "volatile." That's the reason you have to boot up Windows every time you turn your computer on, moving the program from your hard drive to the DRAM chips. But an experimental molecular device Reed made last fall holds data for more than 10 minutes after the power is shut off. "Suppose



ANNE HAMERSKY

Staring at the future: Yale's Reed has measured the properties of single molecules.

we can get that up to several years," says Reed. "It would essentially be nonvolatile memory. Imagine how many times you wouldn't have to boot up Windows."

Although these early applications are worlds away from the billion-transistor molecular computers that enthusiasts envision, they could show the value of organic molecules as an electronic material. "They are a camel's nose under the tent," says Reed, adding that "these hybrid devices are already very realistic. They're the first step down the road to more complex [molecular] circuits."

It's likely, however, to be a long road. Even a simple computer made of molecular components is at least a decade away—and then "only if we get really clever," acknowledges Williams. But the HP chemist says his group is already on its way. In their initial prototypes, the California researchers have fabricated the top and bottom metal wires as perpendicular grids, creating a "crossbar" structure with the molecules sitting at the junctions of the wires. So far, the group has made devices with metal contacts that are thousands of nanometers in diameter; there are millions of molecules at each junction. But Williams says that by later this year the group expects to have wires measuring a few nanometers across. "It didn't make sense to do everything hard right away. So we used much larger wires. Now we're doing the experiments to switch to smaller wires and make the measurements."

The nearly perfect candidates for such tiny wires are structures known as carbon nanotubes. These regularly shaped pipes, only a few nanometers in diameter, could be excellent conduits for electrons speeding through a molecular circuit. The problem is that nanotubes tend to form as a tangled mess—far from the neatly ordered arrays needed to fabricate complex circuits. Building any structures with nanotubes "is now an art form," says physicist Paul McEuen of the University of California, Berkeley. "We basically throw them down on the ground and look for [the structure] we want."

The HP/UCLA group is confident they'll solve the wiring problem. "Eventually nanotubes will be used. Their electronic and physical properties are so desirable," says Williams. For now, he says, the group is also working on silicon nanowires. And, promises Williams, with or without carbon nanotubes, by late summer the scientists will scale down the junctions of devices to smaller than 10 nanometers. The near-term targets are a 16-bit memory that is 100 nanometers on a side, and soon after that a similarly sized logic device. These rudimentary circuits may

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not threaten the reign of silicon, but they could be a milestone in helping prove that molecular electronics is feasible.

But then comes the truly daunting part: turning these simple devices into complex logic circuits, and integrating them into an actual computer. One of the penalties you pay for making microelectronics based on chemistry is that, unlike silicon chips made in high-tech fabrication plants, molecular devices synthesized in vats of chemicals will inherently be full of defects. At the scale of individual molecules, chemistry is given to statistical fluctuations—sometimes it works and sometimes it doesn't. But it's here that the HP/UCLA scientists contend they have made their most important breakthrough.

Their answer: software that overcomes the defects. Several years ago, computer scientists at HP built a supercomputer called Teramac, using defective silicon chips so flawed they were considered worthless. The HP scientists cobbled these rejected chips into a computer by developing a "crossbar" architecture that makes it possible to connect any input with any output. Once the hardware was built, the computer was programmed to identify and route around any defects. The system worked—and its massive parallelism provided an archetype that the California scientists plan to use for their molecular computer.

"A chemist working on a computer is a bizarre thing. You can't go to a chemist and ask them to build a computer," says Heath, one of the UCLA scientists who is helping to synthesize the necessary components. But, he says, the Teramac architecture has provided the HP/UCLA group a clearly defined target. "The software will turn it into a machine," says Heath. That molecular computer "may be a long way off," he acknowledges. "But there's no reason why it won't work."

Today's crude prototypes won't threaten the reign of silicon, but could **help prove** to skeptics that molecular electronics is feasible.

The World Between

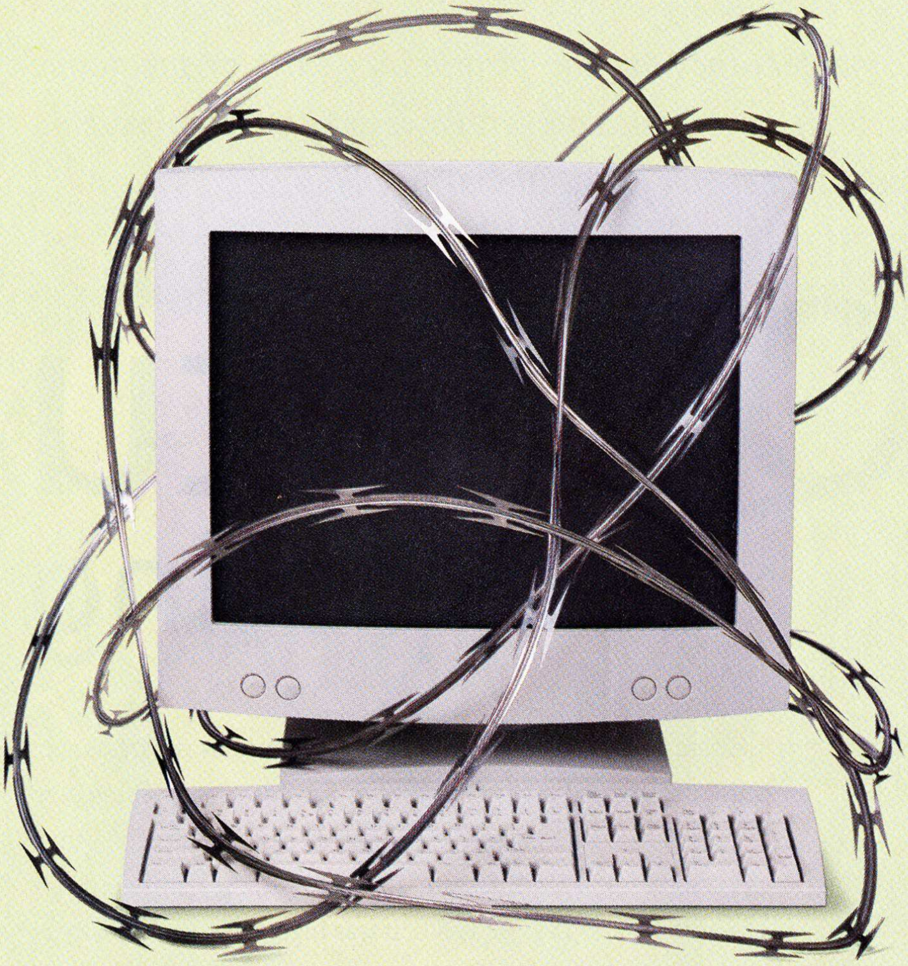
While folks like Heath are sanguine, the technology has its share of doubters. The field of molecular electronics "is in love with itself," says Rick Lytel, a computer scientist at Sun Microsystems. Despite his skepticism, however, Lytel is keeping a sharp eye on the field for Sun and is developing specifications to test and evaluate prototype molecular devices. He believes molecular electronics could eventually find uses as memory devices. But Lytel says many of his colleagues in the field have deluded themselves into thinking that they are "only a step away from the marketplace."

Even believers in the prospects of molecular electronics disagree with one another over the role the technology will play in computation and electronics. Take Mark Ratner, a chemist at Northwestern University who is generally regarded as one of the grandfathers of the field. Ratner doubts molecules will ever compete directly with silicon in complex computational tasks. "You want to use molecules for what they do best" and to compensate for where silicon falls short, says Ratner. In particular, he points to their ability to recognize and respond to other molecules. By combining those functions with the newly developed electronic properties, you might make tiny sensors and actuators that detect and react intelligently to biological and chemical clues. It might, says Ratner, make possible implantable biochips incorporating sensors and actuators made out of molecular electronics that sense the needs of the body and respond by discharging an appropriate dose of medication.

For this pioneer of molecular electronics, the true potential of the field could be realized in bringing the world of microelectronics together with the world of biology and molecules. Molecular electronics, suggests Ratner, could be the piece of the puzzle that finally helps to bridge the material gap between biology and computing. ◊

Molecular Sampler

ORGANIZATION	KEY RESEARCHERS	FOCUS
Delft University of Technology	Cees Dekker	Using carbon nanotubes as nanowires and electronic devices; has built a transistor out of a single nanotube
Harvard University	Charles Lieber	Synthesizing arrays of carbon nanotubes that can act as both wires and electronic devices
Hewlett-Packard/UCLA	R. Stanley Williams, Philip Kuekes (HP); Fraser Stoddart, James Heath (UCLA)	Chemically assembling arrays of reconfigurable switches for memory and logic; goal is to build a molecular computer
IBM Research	Phaedon Avouris	Studying the properties of nanotubes; has made a transistor out of a single nanotube
Rice University	James Tour	Developing a self-assembled computer with a highly interconnected network of logic and memory; has synthesized molecules with desirable properties
University of Colorado	Josef Michl	Building a molecular computer; has made suitable molecules and short wires
Yale University	Mark Reed	Collaborating with Rice University to build a molecular computer; has fabricated molecular switches and memory devices



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Computers that tap the bizarre properties of subatomic particles might calculate with awesome speed—cracking codes that stymie conventional machines.

Quantum Computing

BY M. MITCHELL WALDROP

"EVERY SO OFTEN," SAYS ISAAC CHUANG, SITTING IN HIS OFFICE AT IBM's Almaden Research Center in San Jose, "something new comes along in physics, and everybody says 'Wow!' Then they get caught up in a whirlwind." In the 1970s, the whirlwind was chaos theory. In the late 1980s, it was high-temperature superconductivity. And now?

"Quantum computing," says Chuang, a slender, soft-spoken physicist who has already emerged as one of the leaders in this esoteric-sounding field with potentially enormous impact.

A quantum computer operates by the rules of quantum weirdness, down in the subatomic realm where our everyday intuitions are violated wholesale. This is a world in which an electron can be in two places at once, in which an atomic nucleus can be spinning clockwise and counterclockwise at the same time. It is a bizarre world in which matter itself dissolves into a ghostly blur of possibilities as soon as you try to look at it.

And yet this surreal world is one in which you *can* do computing, insists Chuang, whose group at Almaden is one of several that have demonstrated the basic principles in the lab. If he and his fellow researchers can ever scale up their demonstrations into practical machines, the payoff will be enormous. Quantum computers could tackle problems that would stymie their conventional counterparts—easily cracking, for instance, the most sophisticated encryption schemes now in use.

Hence the new whirlwind. "It's easy for quantum computing to sound like a fanciful theorist's dream," says physicist Neil Gershenfeld of the MIT Media Lab. "But just extrapolating Moore's Law, the scaling relation that says microchips shrink by a factor of two every two years or so, somewhere around the year 2020 or 2030 is when we hit one bit per atom—and when a new semiconductor fabrication plant will cost the gross national product of the planet. So if we really want to keep

PHOTOGRAPH BY ANNE HAMERSKY

Qubit king: Isaac Chuang is spinning a new kind of computer.

getting faster, there aren't many other places to turn. Quantum weirdness is essentially the only resource we have that's still untapped for computing. It's the only big thing that's left in the universe."

A New Kind of Bit

Actually, when quantum computing started out, it *was* a fanciful theorist's dream—the late Richard Feynman's, most notably. The famously whimsical Nobel laureate first started pushing the idea in 1981, following an earlier suggestion by Argonne National Laboratory physicist Paul Benioff. Others quickly followed Feynman's lead. And by the time Ike Chuang first encountered quantum computing in the late 1980s, shortly after receiving his undergraduate physics degree from MIT, a cadre of at least half a dozen physicists and computer scientists were actively working in the field.

Certainly Chuang was smitten. "I've always wanted to know what information is in a physical sense—and to understand what physics is in terms of information," he says. Quantum computing seemed like a completely new way to understand them both.

Take this business of encoding information, he says: The subatomic world is full of *yes-no* choices that make it downright easy. Most particles—including electrons, protons and even the ephemeral packets of light called photons—possess a kind of built-in rotary motion known as "spin." So if your subatomic computer used electrons, for example, you could say that an electron spinning in one direction represented a binary 1, while an electron spinning in the opposite direction represented a 0. And once you encode the information, says Chuang, the subatomic world also offers any number of ways to process it. By manipulating the magnetic environment of electrons, say, or by routing photons through an array of polarizers, mirrors and beam splitters, you could subject your quantum bits to all the operations required by a digital computer.

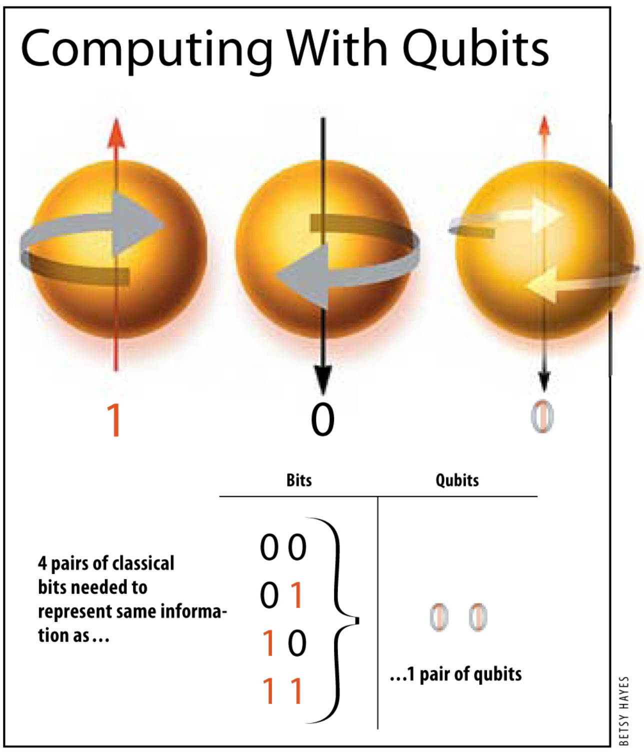
But there would also be a critical difference. Conventional computers followed the rules of binary logic, governed by an ironclad *either-or* distinction: Each bit of information is either *true* or *false, on* or *off, one* or *zero*. To enforce this distinction, conventional machines represent each bit as the presence or absence of a few zillion electrons collected in a tiny silicon transistor, so that the zillions are either there or they are not.

But once you get down to the level of individual particles, says Chuang, almost nothing is absolute. An electron, for example, could be spinning one way or the other—but it could also exist as a kind of mixture of spins. According to the laws of quantum physics, you could say the electron has a *probability* of spinning one way or the other. But unless you actually made a measurement and forced the issue, you couldn't *know* which it was; in a sense, the electron itself would be undecided. And that, in turn, means that each bit of quantum information could be undecided. Instead of being *either-or*, a quantum "qubit" could be *both-and:* representing 0 and 1 simultaneously.

> "Quantum weirdness is the only resource that's still untapped for computing. It's the only **big thing** that's left in the universe." —Neil Gershenfeld, MIT

This ambiguity has a powerful consequence that becomes more apparent when you think of not one but two qubits. These qubits could simultaneously exist as a combination of all possible two-bit numbers: (00), (01), (10) and (11). Add a third qubit and you could have a combination of all possible three-bit numbers: (000), (001), (010), (011), (100), (101), (110) and (111). This kind of system scales exponentially: n qubits can stand for 2^n numbers at once. Line up a mere 40 qubits, and you could represent every binary number from zero to more than a trillion—simultaneously.

Furthermore, says Chuang, just as a collection of quantum qubits could represent a huge array of numbers simultaneously, a quantum computer could process every possible input simultaneously—the most perfect form of parallel processing imaginable. Given the right kind of problem and a sufficient supply of qubits, a quantum computer could outpace its conventional counterparts by many orders of magnitude. "I read about all this," says Chuang, remembering his first encounter with Feynman's articles around 1987 or so, "and from then on, I wanted to build a quantum computer."



BETSY HAYES

Conventional bits are either 1 or 0—in this scheme, represented by a subatomic particle spinning one way or the other. A quantum computer works from the ambiguous reality: Spin direction is a matter of probability.

Algorithm Attack

But how? Feynman and the other theoreticians had focused on quantum computing as a mathematical abstraction—and with good reason. "Building a real quantum computer is a viciously

difficult task," says Chuang. Everything depends on making sure the qubits retain their incredibly fragile quantum-mechanical mix of 1 and 0—what physicists refer to as staying "coherent." One bump from a stray air molecule, one twitch in the magnetic field, one ricochet of a random photon, and coherency vanishes. Let that happen in a quantum computer and your qubits will instantly collapse from *both-and* to *either-or*—meaning that you will suddenly find yourself looking at an ordinary computer full of ordinary 1s and 0s.

"Quantum mechanics goes away when you look at it," sighs Chuang. "So you have to make sure that the computer is extremely well isolated from the rest of the world." But the isolation can't be total, either, since you still need to put data in and read out the results. "This," Chuang declares, "is the discord that stalks quantum computing. How can you control it if, at the same time, you have to leave it alone?"

As the 1980s became the 1990s, many researchers continued to grapple with the problem. Chuang even made it the subject of his doctoral dissertation at Stanford. But nothing they proposed seemed feasible. And with no compelling application at hand, quantum computing seemed destined for the same cul-de-sac as countless other exotic pieces of science.

Two developments—one theoretical, one practical—have rescued quantum computing from irrelevancy, explains MIT physicist Seth Lloyd. On the theoretical side, it was a factoring algorithm discovered by Peter Shor of AT&T Research labs—an achievement that went right to the heart of modern cryptography. In most current encryption schemes, including those used to send credit-card numbers and other sensitive information across the Internet, an eavesdropper can break the code of a given message only by factoring a very large number. Now, factoring small numbers is trivial—grade school kids learn that 12 = 2 x 2 x 3. But factoring large numbers is one of the quintessentially hard problems in computer science. No matter how clever the algorithms, in fact, the time required to factor larger and larger numbers grows exponentially. Go beyond a few hundred digits, and even the fastest machines in the world will be overwhelmed: The factoring time will vastly exceed the lifetime of the universe.

Or rather, it will with a conventional computer. Shor proved that a quantum computer could factor large numbers in a time that increases only as some power of the numbers' size—rapid growth, to be sure, but not remotely as explosive as exponential growth. Indeed, a conventional computer would need to crank away for billions of years to factor a 400-digit number. A quantum machine could do the job in about a year. The implication was that "unbreakable" codes might now be breakable. And with that announcement, the National Security Agency, the Pentagon, the cryptography community, and indeed, the whole computer community woke up to the fact that quantum computing wasn't a theorist's plaything anymore. Peter Shor was holding out the possibility of a real and critically important application.

Spin doctor: MIT's Neil Gershenfeld flips nuclear spins with magnets.

Meanwhile, on the experimental side, quantum computing was beginning to look much more possible in the lab. In 1993, for example, Lloyd brought the mathematical abstractions down to earth when he showed how quantum computation could be carried out by qubits arranged in a regular array—just the kind of quantum computer that might actually get built. Then in 1996, Chuang and MIT's Gershenfeld made things even more concrete when they suddenly saw a way to build it.

"I went into Ike's office on a Monday and didn't emerge until Friday," laughs Gershenfeld, thinking back to the quantum computing conference that brought

PHOTOGRAPH BY FURNALD/GRAY

him to the University of California at Santa Barbara and the Institute for Theoretical Physics, where Chuang had a postdoc appointment. "We got this feeling that comes along only rarely, that there was this beautiful structure already existing in the world, and that we were seeing it for the first time."

"Quantum mechanics goes away when you look at it. How can you control it if you have to leave it alone?" —Isaac Chuang, IBM Research

That structure became apparent as soon as they decided to forget about electrons or photons, and instead make their qubits at the heart of the atom: the nucleus. Actually, it is the nucleus's building blocks—protons and neutrons—that have spin. While individual spins tend to pair up and cancel each other out, in some isotopes a few are left over, leaving a net spin in one direction or another.

Nuclear qubits were appealing for several reasons. First, you can make a perfectly fine qubit out of any nuclear isotope that has a spin—as many do. Second, says Gershenfeld, "this is the most coherent system in the universe." Every nucleus is protected from outside disturbances by its dense cloud of electrons. That means that once you get its spin lined up, it will stay that way for hours or days—an eon in computer time. Third, nuclear qubits are incredibly easy to assemble. "Instead of trying to nanofabricate nanostructures," says Gershenfeld, "we can just use the ones nature gave us: molecules." Moreover, he points out, the nuclear spins inside a given molecule tend to interact nicely. Take chloroform, for example, a molecule consisting of a carbon atom attached to three chlorine atoms and one hydrogen atom: When the hydrogen nucleus and the carbon nucleus are spinning the same way, their energy levels will be measurably different from when they are spinning opposite from one another.

Finally, says Gershenfeld, the technology for manipulating these nuclear spins is already very mature. It's called nuclear magnetic resonance, or NMR, and it is routinely used in chemical analysis and in hospital magnetic resonance imaging scanners. It's a simple matter to adapt commercial NMR spectrometers to do quantum computing.

Say you want to carry out a logical operation using chloroform—something like, "If carbon is 1, then hydrogen is 0." You just suspend the chloroform molecules in a solvent, and put a sample in the spectrometer's main magnetic field to line up the nuclear spins. Then you hit the sample with a brief radio-frequency pulse at just the right frequency. The hydrogen spin will either flip or not flip, depending on what the carbon is doing—exactly what you want for an *if-then* operation. By hitting the sample with an appropriately timed sequence of such pulses, moreover, you can carry out an entire quantum algorithm—without ever once having to peek at the nuclear spins and ruin the quantum coherence.

So there it was, Chuang and Gershenfeld realized: NMR was a natural for quantum computing. They were not alone. Chuang remembers being "surprised and delighted" to learn that Harvard University NMR expert David Cory and his colleagues were independently making exactly the same proposal. For researchers of Cory's caliber to enter the field constituted more of an endorsement of the NMR idea than a rivalry, Chuang believed. In any case, there was plenty of work to go around. By this point, Lloyd recalls, with researchers having identified a real application for quantum computing plus a feasible technique for making it work, "all hell was breaking loose" in the field. "All of a sudden there was this wonderful new game to play."

The game has only gotten better. In just the past few years, for example, Shor and others have shown that quantum computers needn't be as fragile as researchers once feared; a variety of quantum error-correction schemes will allow the devices to undo the damage caused by environmental perturbations and restore their qubits to full coherence. Lov Grover of Lucent Technologies' Bell Labs has discovered a quantum search algorithm that is substantially faster than its best classical counterpart. Chuang himself has used NMR to demonstrate Grover's algorithm, first on a two-qubit quantum computer—a chloroform molecule—and more recently on a three-qubit molecule. Along the way, Chuang and Gershenfeld's partnership has expanded into a nationwide consortium for quantum computing research, including members from MIT, Stanford, the University of California at Berkeley, IBM and several other industrial partners. Cory's team, which is working on an NMR demonstration of Shor's algorithm, has likewise broadened into a Harvard-MIT collaboration. Both groups are among those getting money from the Defense Advanced Research Projects Agency—the arm of the Defense Department that essentially invented the Internet—as part of the first significant federal funding initiative for quantum computing.

Making "Magic"

None of this means that we'll be trading in our PCs for quantum laptops anytime soon. Quantum computing is barely into its proof-of-principle stage, with a long way to go before it evolves even to the qubit equivalent of World War II-era vacuum-tube machines like the ENIAC. Much more likely are quantum add-ons to conventional machines—"coprocessors" that will perform specific tasks in the same way that a graphics card takes over the most difficult display chores.

What exactly those tasks will be, however, is an unsettled question. MIT physicist Edward Farhi points out that the study of quantum algorithms is still in its infancy. The two best ones discovered so far—Shor's and Grover's—will doubtless be followed by many more, opening up applications that go well beyond factoring and searching. Nonetheless, says Farhi, "a quantum computer isn't necessarily fast. It's a device that attacks problems in a different way. We're still trying to understand what makes a problem amenable to that kind of attack. You have to choose your problem carefully to take advantage of the quantum magic."

In practice, adds Farhi, how quantum coprocessors are used could depend a lot on how much they cost. And that's a complicated issue. At IBM Almaden, for

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example, the core of Chuang's quantum computer is small and inexpensive: qubit-containing molecules dissolved in a few drops of colorless solvent, encased in a glass tube smaller than his little finger. But the NMR spectrometer that makes the computer go is a silvery, 10-foot-tall cylinder surrounded by great thickets of wires and plumbing—most of it required to service the liquid helium that chills the spectrometer's superconducting magnets. If future quantum coprocessors follow this pattern, they will be huge, multimillion-dollar behemoths that fill up whole rooms, and that only governments can afford. In that case, quantum computers may well be restricted to hard-core national security tasks such as cryptography and intelligence-gathering.

But such an outsized contraption may not be inevitable. Gershenfeld's group at the MIT Media Lab is working on a compact, room-temperature NMR computer. They hope this device will be a prototype of a quantum coprocessor that will power inexpensive little gadgets—peripherals that will sit on the desktop like a modern-day printer or scanner. If *that* proves to be the pattern, then we could see a new generation of quantum hackers going to work in much the same way their forebears did at the beginning of the personal computer revolution, creating a profusion of innovative quantum software.

In the meantime, however, Chuang and his fellow experimenters are far less concerned with their machines' physical size than with their qubit count. "The first year we had lots of wonderful one-qubit machines popping up all over the place," he says. "Now at IBM we have a three-qubit computer, and we're planning even larger computers." In March, Los Alamos National Laboratory announced a seven-qubit NMR computer, and Chuang is confident that one lab or another will soon be demonstrating molecules with as many as 10 qubits. He concedes that this will be a tricky task, however. "Say I want a molecule with certain properties. When I draw it and go to the chemists, they just laugh: 'That's not real!' They call it a 'physicist's molecule.'" One complication is that carbon, the key ingredient of all complex molecules, almost invariably occurs as the isotope carbon-12—which is spinless. Chuang's chloroform computer worked only because its molecules were made with the rare and expensive isotope carbon-13, which does spin.

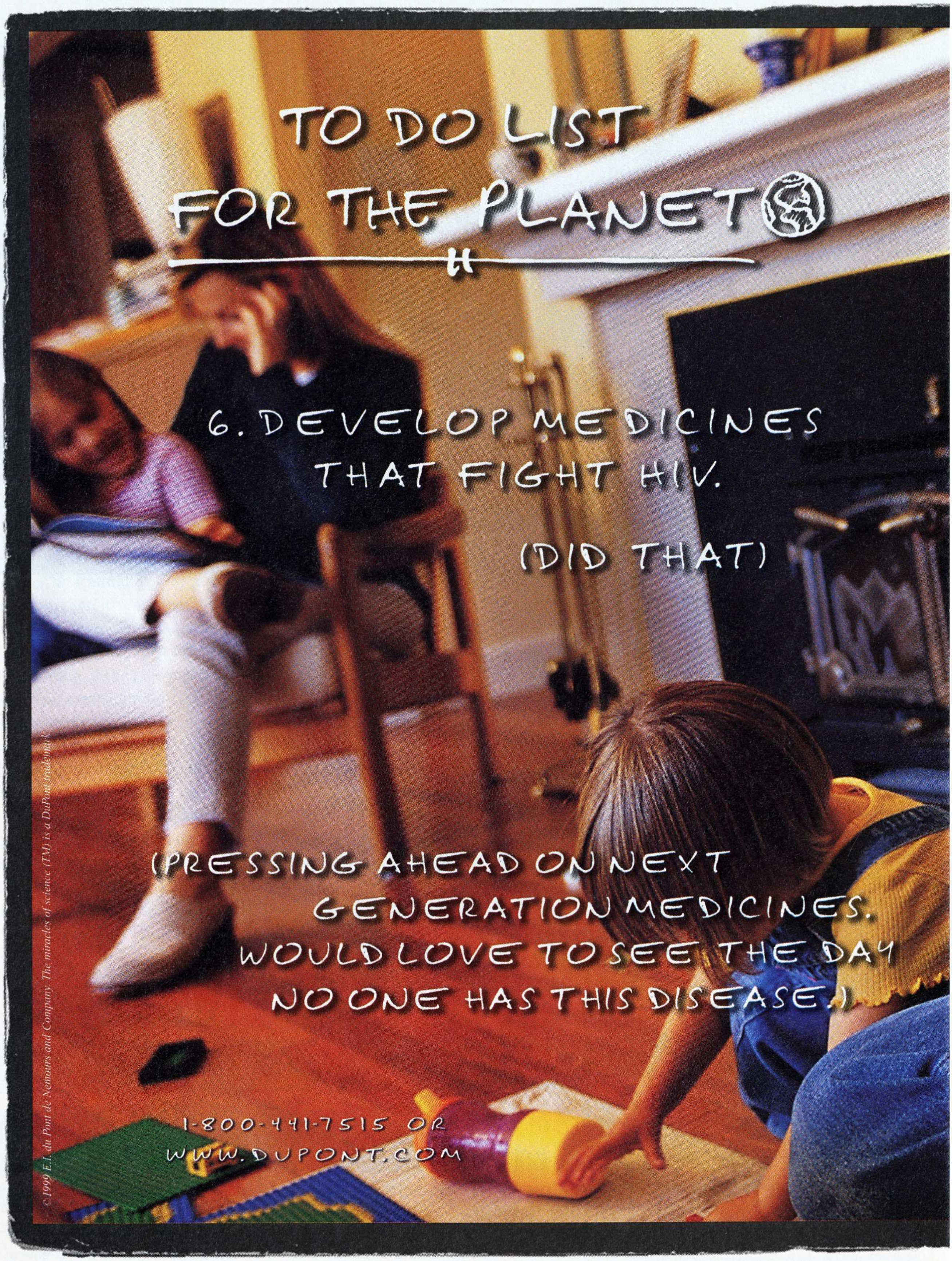
Yet a truly useful quantum computer will need hundreds or even thousands of qubits. Presumably, says Chuang, that means some kind of long-chain polymer. But developing the right kind of polymer, figuring out how to stabilize it, and then learning how to do NMR with it—that all adds up to many more years of research. And that's *if* NMR is the final answer for quantum computing—a prospect that is no more guaranteed than that vacuum tubes were the final answer for conventional electronic computers. Ultimately, a practical quantum device might take some other form entirely. In the "ion trap" approach, for example, the qubits are ionized atoms suspended in an oscillating electric field. This approach has proved fiendishly difficult to implement, despite some preliminary success by physicist Christopher R. Monroe and his team at the National Institute of Standards and Technology in Boulder, Colo. But if the ion trap idea ever pans out, it will be a remarkably clean and elegant system to program. Alternatively, there are "quantum dots" in which the qubits would be electrons trapped in an array of tiny structures etched onto the surface of a silicon crystal *(see "Quantum Dot Com,"* TR *January/February 2000)*. Then there is the liquid crystal approach, the crystal lattice approach—on and on.

The myriad possibilities are limited only by your imagination, says Gershenfeld—which is precisely why quantum computing has stirred up so much excitement. "This has the feel of being a whole new science," he declares. "Computer scientists are having to learn physics, and that doesn't quite fit into their intellectual framework. Physicists are having to learn computer science, and that doesn't quite fit into *their* framework. Quantum computing breaks down the institutional boundaries at almost any institution you can name. And every side is the richer for learning a new language for describing the world."

But perhaps an even deeper reason for the excitement is the way quantum computing expands our intellectual horizons. "I'm not just doing this for the sake of quantum computing," says Chuang. "I'm doing it because so little is known about computing in general. For 50 years we've just focused on one technique in computing": that is, microchips based on the on-off dichotomy of binary logic. The pursuit of quantum computing, Chuang believes, addresses a fundamental issue: "What does it take to perform a computation—and how can we manipulate nature's laws to perform the computation we want? That is the more basic question that quantum computing brings out." ◊

On the Quantum Quest

ORGANIZATION	KEY RESEARCHERS	WEB SITE	FOCUS
IBM/MIT/Berkeley/Stanford	Isaac Chuang (IBM) Neil Gershenfeld (MIT)	squint.stanford.edu/ www.almaden.ibm.com/st/projects/quantum/intro/	"Enabling technology" for NMR-based quantum computing; scale up to 10-40 qubits
Harvard/MIT/Los Alamos	David Cory (Harvard)	mrix4.mit.edu/Cory/Cory.html	Quantum algorithms and NMR-based systems
NIST	Christopher R. Monroe	www.bldrdoc.gov/timefreq/ion/index.htm	Ion-trap quantum computing; demonstrated a two-qubit device using trapped barium ions
Caltech/MIT/USC	Seth Lloyd (MIT) M. Despain (USC) H. Jeff Kimble, John Preskill, and Steven Koonin (Caltech)	www.theory.caltech.edu/~quic/ Quantum	Algorithms and quantum error correction
Oxford University	David Deutsch, Jonathan Jones	www.qubit.org/	Ion-trap and NMR implementations; quantum information theory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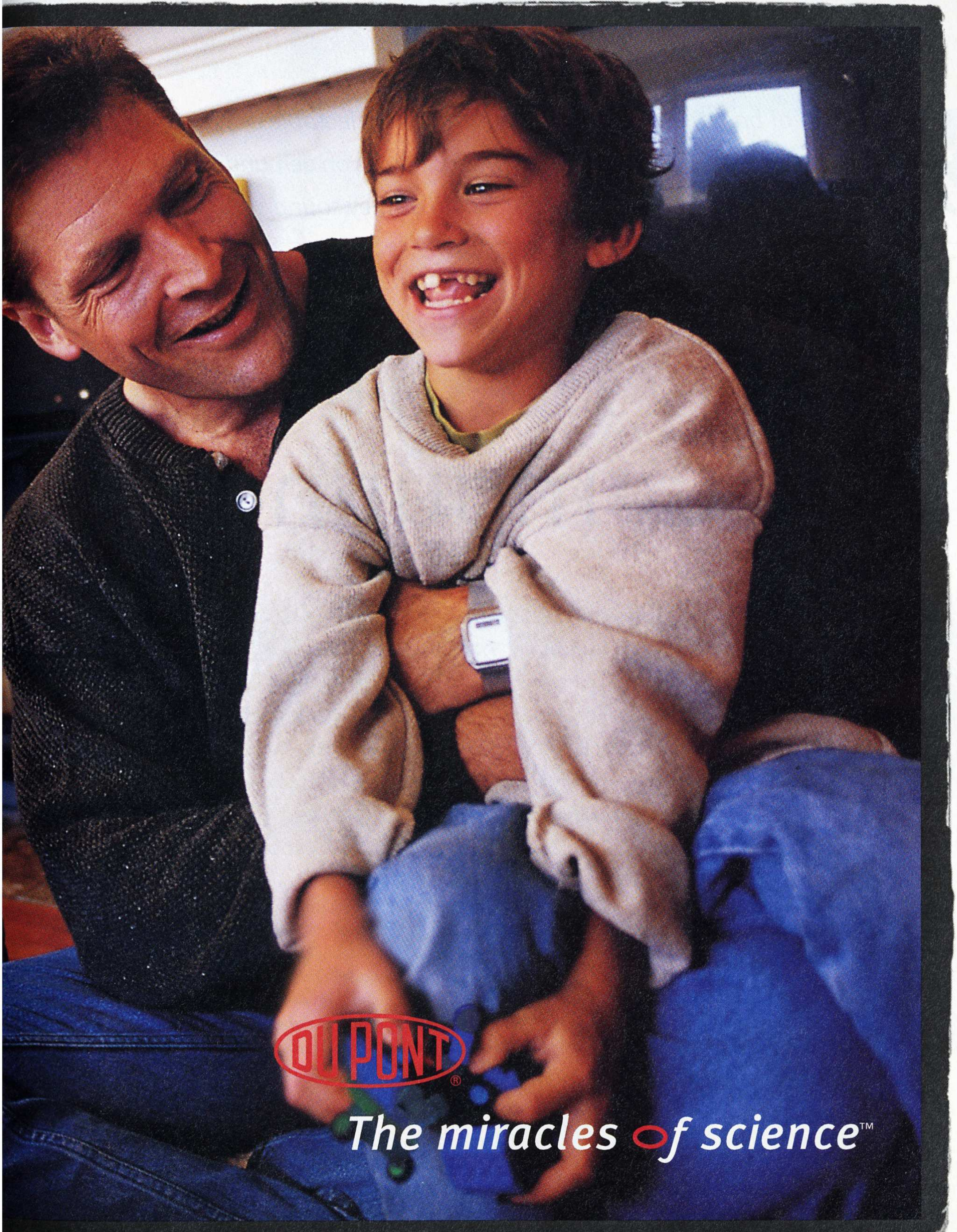

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A vial of bacteria capable of computation? Injectable cells that survey the bloodstream and produce drugs on demand? These ideas might not be as far-fetched as they sound.

BY SIMSON L. GARFINKEL

Biological Computing

TODAY'S SILICON-BASED MICROPROCESSORS ARE MANUFACtured under the strictest of conditions. Massive filters clean the air of dust and moisture, workers don spacesuit-like gear and the resulting systems are micro-tested for the smallest imperfection. But at a handful of labs across the country, researchers are building what they hope will be some of tomorrow's computers in environments that are far from sterile—beakers, test tubes and petri dishes full of bacteria. Simply put, these scientists seek to create cells that can compute, endowed with "intelligent" genes that can add numbers, store the results in some kind of memory bank, keep time and perhaps one day even execute simple programs.

All of these operations sound like what today's computers do. Yet these biological systems could open up a whole different realm of computing. "It is a mistake to envision the kind of computation that we are envisioning for living cells as being a replacement for the kinds of computers that we have now," says Tom Knight, a researcher at the MIT Artificial Intelligence Laboratory and one of the leaders in the biocomputing movement. Knight says these new computers "will be a way of bridging the gap to the chemical world. Think of it more as a process-control computer. The computer that is running a chemical factory. The computer that makes your beer for you."

As a bridge to the chemical world, biocomputing is a natural. First of all, it's extremely cost-effective. Once you've programmed a single cell, you can grow billions more for the cost of simple nutrient solutions and a lab technician's time. In the second place, biocomputers might ultimately be far more reliable than computers built from wires and silicon, for the same reason that our brains can survive the death of millions of cells and still function, whereas your Pentium-powered PC will seize up if you cut one wire. But the clincher is that every cell has a miniature

PHOTOGRAPHS BY JOHN SOARES

Knight vision:
Tom Knight sees great possibilities for computers built into cells.

chemical factory at its command: Once the organism was programmed, virtually any biological chemical could be synthesized at will. That's why Knight envisions biocomputers running all kinds of biochemical systems and acting to link information technology and biotechnology.

Realizing this vision, though, is going to take a while. Today a typical desktop computer can store 50 billion bits of information. As a point of comparison, Tim Gardner, a graduate student at Boston University, recently made a genetic system that can store a single bit of information—either a 1 or a 0. On an innovation timeline, today's microbial programmers are roughly where the pioneers of computer science were in the 1920s, when they built the first digital computers.

Indeed, it's tempting to dismiss this research as an academic curiosity, something like building a computer out of Tinker Toys. But if the project is successful the results could be staggering. Instead of painstakingly isolating proteins, mapping genes and trying to decode the secrets of nature, bioengineers could simply program cells to do whatever was desired—say, injecting insulin as needed into a diabetic's bloodstream—much the way that a programmer can manipulate the functions of a PC. Biological machines could usher in a whole new world of chemical control.

In the long run, Knight and others say, biocomputing could create active Band-Aids capable of analyzing an injury and healing the damage. The technology could be used to program bacterial spores that would remain dormant in the soil until a chemical spill occurred, at which point the bacteria would wake up, multiply, eat the chemicals and return to dormancy.

In the near term—perhaps within five years—"a soldier might be carrying a biochip device that could detect when some toxin or agent is released," says Boston University professor of biomedical engineering James Collins, another key player in the biocomputing field.

The New Biology

Biocomputing research is one of those new disciplines that cuts across well-established fields—in this case computer science and biology—but doesn't fit comfortably into either culture. "Biologists are trained for discoveries," says Collins. "I don't push any of my students towards discovery of a new component in a biological system." Rockefeller University postdoctoral fellow Michael Elowitz explains this difference in engineering terms: "Typically in biology, one tries to reverse-engineer circuits that have already been designed and built by evolution." What Collins, Elowitz and others want to do instead is forward-engineer biological circuits, or build novel ones from scratch.

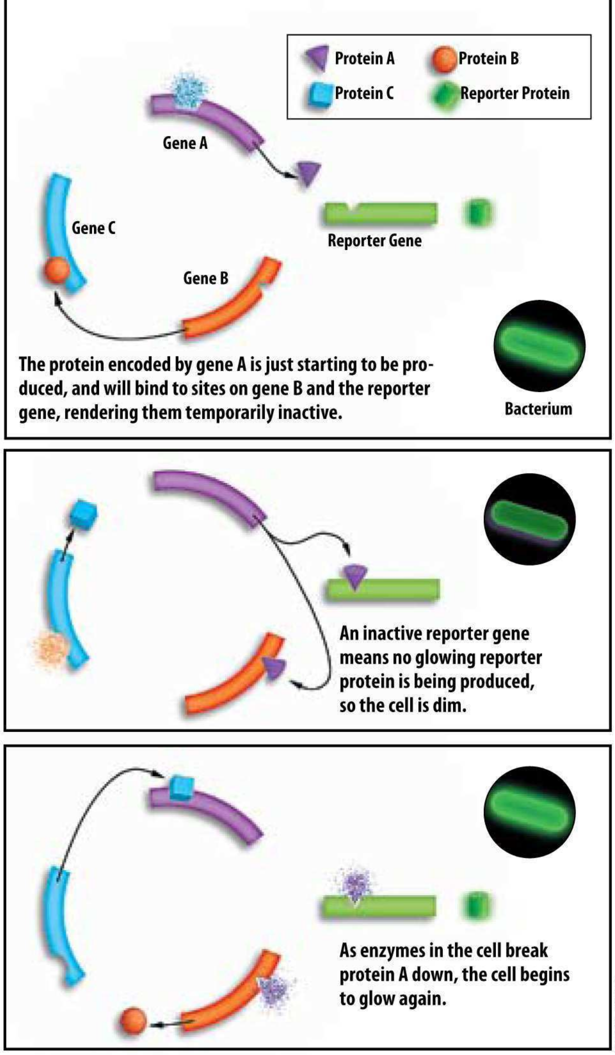
But while biocomputing researchers' goals are quite different from those of cellular and molecular biologists, many of the tools they rely on are the same. And working at a bench in a biologically oriented "wet lab" doesn't come easy for computer scientists and engineers—many of whom are used to machines that faithfully execute the commands that they type. But in the wet lab, as the saying goes, "the organism will do whatever it damn well pleases."

After nearly 30 years as a computer science researcher, MIT's Knight began to set up his biological lab three years ago, and nothing worked properly. Textbook reactions were failing. So after five months of frustratingly slow progress, he hired a biologist from the University of California, Berkeley, to come in and figure out what was wrong. She flew cross-country bearing flasks of reagents, biological samples—even her own water. Indeed, it turned out that the water in Knight's lab was the culprit: It wasn't pure enough for gene splicing. A few days after that diagnosis, the lab was up and running.

Boston University's Gardner, a physicist turned computer scientist, got around some of the challenges of setting up a lab by borrowing space from B.U. biologist Charles Cantor, who has been a leading figure in the Human Genome Project. But before Gardner turned to the flasks, vials and culture dishes, he spent the better part of a year working with Collins to build a mathematical model for their genetic one-bit switch, or "flip-flop." Gardner then set about the arduous task of realizing that model in the lab.

The flip-flop, explains Collins, is built from two genes that are mutually antagonistic: When one is active, or "expressed," it turns the second off, and vice versa. "The idea is that you can flip between these two states with some external influence," says Collins. "It might be a blast of a chemical or a change in temperature." Since one of the

A Clock in a Cell



The "ticking" of this bacterial clock is a visual phenomenon—the bacterium glows and dims as the production of a fluorescent "reporter" protein is turned on and off. The gene for this reporter protein is controlled by three other genes—A, B and C—that work together in a cycle: Protein A (encoded by gene A) represses gene B, protein B represses gene C, and protein C represses gene A. Since protein A also turns off the reporter gene, this cycle ultimately controls the timing of the clock.

two genes produces a protein that fluoresces under laser light, the researchers can use a laser-based detector to see when a cell toggles between states.

In January, in the journal *Nature*, Gardner, Collins and Cantor described five such flip-flops that Gardner had built and inserted into *E. coli*. Gardner says that the flip-flop is the first of a series of so-called "genetic applets" he hopes to create. The term "applet" is borrowed from contemporary computer science: It refers to a small program, usually written in the Java programming language, which is put on a Web page and performs a specific function. Just as applets can theoretically be combined into a full-fledged program, Gardner believes he can build an array of combinable genetic parts and use them to program cells to perform new functions. In the insulin-delivery example, a genetic applet that sensed the amount of glucose in a diabetic's bloodstream could be connected to a second applet that controlled the synthesis of insulin. A third applet might enable the system to respond to external events, allowing, for example, a physician to trigger insulin production manually.

Within a few months, James Collins hopes to launch a **biocomputing company.** Its early products might detect toxins or food contamination.

GeneTic Tock

As a graduate student at Princeton University, Rockefeller's Michael Elowitz constructed a genetic applet of his own—a clock.

In the world of digital computers, the clock is one of the most fundamental components. Clocks don't tell time—instead, they send out a train of pulses that are used to synchronize all the events taking place inside the machine. The first IBM PC had a clock that ticked 4.77 million times each second; today's top-of-the-line Pentium III computers have clocks that tick 800 million times a second. Elowitz's clock, by contrast, cycles once every 150 minutes or so.

The biological clock consists of four genes engineered into a bacterium *(see "A Clock in a Cell," p. 72)*. Three of them work together to turn the fourth, which encodes for a fluorescent protein, on and off—Elowitz calls this a "genetic circuit."

Although Elowitz's clock is a remarkable achievement, it doesn't keep great time—the span between tick and tock ranges anywhere from 120 minutes to 200 minutes. And with each clock running separately in each of many bacteria, coordination is a problem: Watch one bacterium under a microscope and you'll see regular intervals of glowing and dimness as the gene for the fluorescent protein is turned on and off, but put a mass of the bacteria together and they will all be out of sync.

Elowitz hopes to learn from this tumult. "This was our first attempt," he says. "What we found is that the clock we built is very noisy—there is a lot of variability. A big question is what the origin of that noise is and how one could circumvent it. And how, in fact, real circuits that are produced by evolution are able to circumvent that noise."

While Elowitz works to improve his timing, B.U.'s Collins and Gardner are aiming to beat the corporate clock. They've filed for patents on the genetic flip-flop, and Collins is speaking with potential investors, working to form what would be the first biocomputing company. He hopes to have funding in place and the venture launched within a few months.

The prospective firm's early products might include a device that could detect food contamination or toxins used in chemical or biological warfare. This would be possible, Collins says, "if we could couple cells with chips and use them—external to the body—as sensing elements." By keeping the modified cells outside of the human body, the startup would skirt many Food and Drug Administration regulatory issues and possibly have a product on the market within a few years. But Collins' eventual goal is gene therapy—placing networks of genetic applets into a human host to treat such diseases as hemophilia or anemia.

Another possibility would be to use genetic switches to control biological reactors—which is where Knight's vision of a bridge to the chemical world comes in. "Larger chemical companies like DuPont are moving towards technologies where they can use cells as chemical factories to produce proteins," says Collins. "What you can do with these control circuits is to

Addressing the Problem

Before they can turn living organisms into computational systems, biocomputing researchers need a way to create and connect multiple "circuits"—switches, clocks and so forth—within a single cell. That's the thrust of the research of Adam Arkin, who works at the University of California, Berkeley, and the nearby Lawrence Berkeley National Laboratory.

"The idea is to make it a generic type of switch," explains Arkin, "where the wires to the inputs and outputs are easily modified genetically, where there is component standardization—meaning we can reuse components within the same circuitry."

But reusing components within a silicon chip is a simpler proposition than reusing circuits within a living cell: A hardware engineer can arrange wires and silicon traces so that a particular circuit is directly connected to another circuit. Inside a cell, however, the genes and proteins float in a molecular soup where they can potentially be affected by just about every other gene and protein in the cell. To get around this problem, Arkin is developing techniques for identifying different circuits inside the cell. If each circuit is given a different address—sort of like an apartment number in a large condominium complex—multiple copies of the same switch could be put inside a single bacterium and activated separately.

A biologist by training, Arkin specializes in modeling complex biological systems from an engineering perspective. "I've tried to be as…rigorous as possible," he says, down to the point of knowing where every atom in a system is. It's this degree of modeling that will be necessary to make the biological-based computing actually work.

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Forward engineers: Tim Gardner (left) and James Collins want to "program" cells at will.

regulate the expression of different genes to produce your proteins of interest." Bacteria in a large bioreactor could be programmed to make different kinds of drugs, nutrients, vitamins—or even pesticides. Essentially, this would allow an entire factory to be retooled by throwing a single genetic switch.

Amorphous Computing

Two-gene switches aren't exactly new to biology, says Roger Brent, associate director of research at the Molecular Sciences Institute in Berkeley, Calif., a nonprofit research firm. Brent—who evaluated biocomputing research for the Defense Advanced Research Projects Agency—says that genetic engineers "have made and used such switches of increasing sophistication since the 1970s. We biologists have tons and tons of cells that exist in two states" and change depending on external inputs.

For Brent, what's most intriguing about the B.U. researchers' genetic switch is that it could be just the beginning. "We have two-state cells. What about four-state cells? Is there some good there?" he asks. "Let's say that you could get a cell that existed in a large number of independent states and there were things happening inside the cell...which caused the cell to go from one state to another in response to different influences," Brent continues. "Can you perform any meaningful computation? If you had 16 states in a cell and the ability to have the cell communicate with its neighbors, could you do anything with that?"

By itself, a single cell with 16 states couldn't do much. But combine a billion of these cells and you suddenly have a system with 2 gigabytes of storage. A teaspoon of programmable bacteria could potentially have a million times more memory than today's largest computers—and potentially billions upon billions of processors. But how would you possibly program such a machine?

Programming is the question that the Amorphous Computing project at MIT is trying to answer. The project's goal is to develop techniques for building self-assembling systems. Such techniques could allow bacteria in a teaspoon to find their

neighbors, organize into a massive parallel-processing computer and set about solving a computationally intensive problem—like cracking an encryption key, factoring a large number or perhaps even predicting weather.

Researchers at MIT have long been interested in methods of computing that employ many small computers, rather than one super-fast one. Such an approach is appealing because it could give computing a boost over the wall that many believe the silicon microprocessor evolution will soon hit *(see "The End of Moore's Law?" p. 42)*. When processors can be shrunk no further, these researchers insist, the only way to achieve faster computation will be by using multiple computers in concert. Many artificial intelligence researchers also believe that it will only be possible to achieve true machine intelligence by using millions of small, connected processors—essentially modeling the connections of neurons in the human brain.

On a wall outside of MIT computer science and engineering professor Harold Abelson's fourth-floor office is one of the first tangible results of the Amorphous Computing effort. Called "Gunk," it is a tangle of wires, a colony of single-board computers, each one randomly connected with three other machines in the colony. Each computer has a flashing red light; the goal of the colony is to synchronize the lights so that they flash in unison. The colony is robust in a way traditional computers are not: You can turn off any single computer or rewire its connection without changing the behavior of the overall system. But though mesmerizing to watch, the colony doesn't engage in any fundamentally important computations.

Five floors above Abelson's office, in Knight's biology lab, researchers are launching a more extensive foray into the world of amorphous computation: Knight's students are developing techniques for exchanging data between cells, and between cells and larger-scale computers, since communication between components is a fundamental requirement of an amorphous system. While Collins' group at B.U. is using heat and chemicals to send instructions to their switches, the Knight lab is working on a communications system based on bioluminescence—light produced by living cells.

> The DNA-based prototypes biocomputing researchers build today may be steppingstones to computers based on neurochemistry, Roger Brent says.

To date, work has been slow. The lab is new and, as the water-purity experience showed, the team is inexperienced in matters of biology. But some of the slowness is also intentional: The researchers want to become as familiar as possible with the biological tools they're using in order to maximize their command of any system they eventually develop. "If you are actually going to build something that you want to control—if we have this digital circuit that we expect to have somewhat reliable behavior—then you need to understand the components," says graduate student Ron Weiss. And biology is fraught with fluctuation, Weiss points out. The precise amount of a particular protein a bacterial cell produces depends not only on the bacterial strain and the DNA sequence engineered into the cell, but also on environmental conditions such as nutrition and timing. Remarks Weiss: "The number of variables that exist is tremendous."

To get a handle on all those variables, the Knight team is starting with in-depth characterizations of a few different genes for luciferase, an enzyme that allows fireflies and other luminescent organisms to produce light. Understanding the light-generation end of things is an obvious first step toward a reliable means of cell-to-cell communication. "There are cells out there that can detect light," says Knight. "This might be a way for cells to signal to one another." What's more, he says, "if these cells knew where they were, and were running as an organized ensemble, you could use this as a way of displaying a pattern." Ultimately, Knight's team hopes that vast ensembles of communicating cells could both perform meaningful computations and have the resiliency of Abelson's Gunk—or the human brain.

Who's Who in Biocomputing

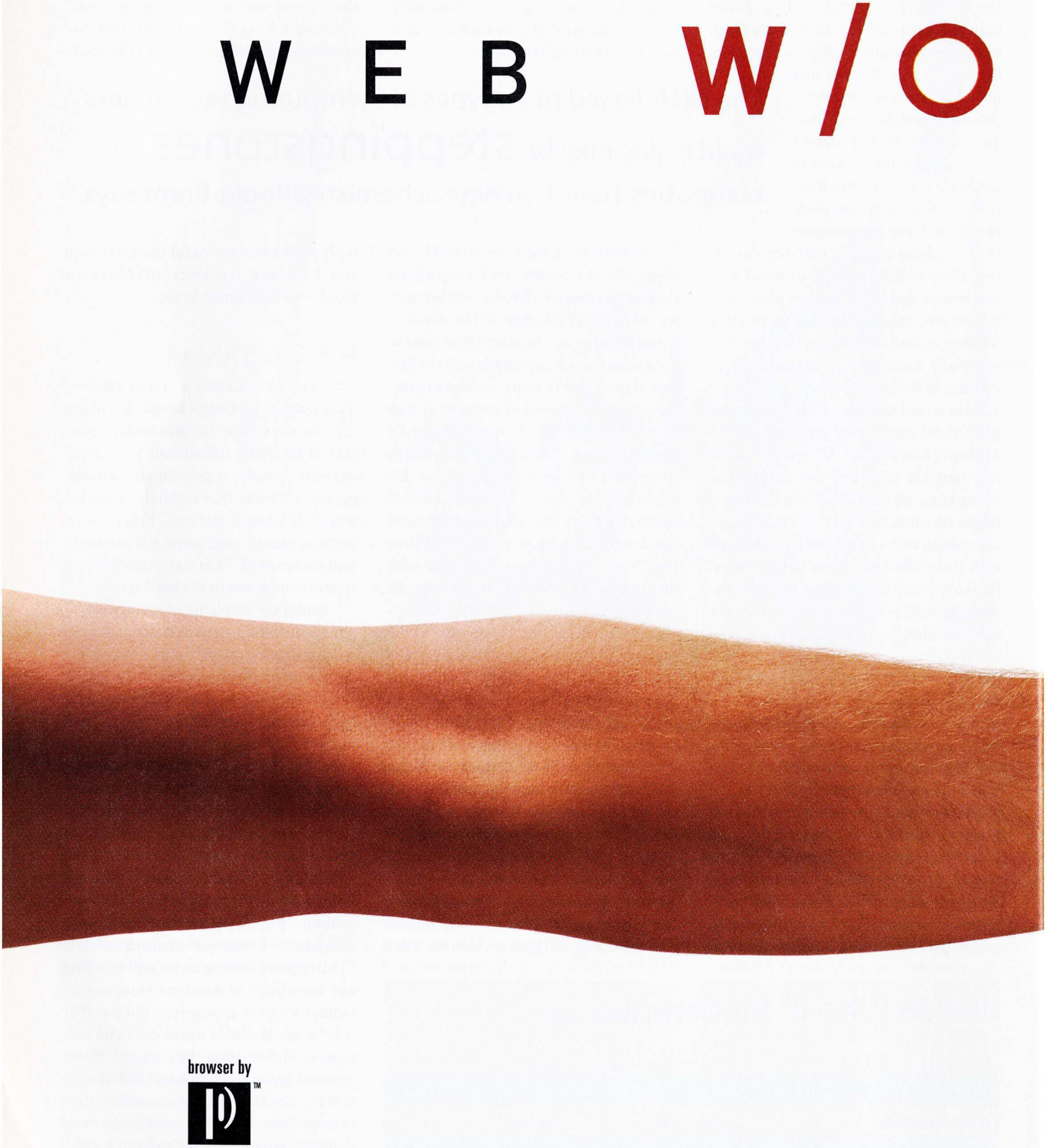
ORGANIZATION	KEY RESEARCHER	FOCUS
Lawrence Berkeley National Laboratory	Adam Arkin	Genetic circuits and circuit addressing
Boston University	James J. Collins	Genetic applets
Rockefeller University	Michael Elowitz	Genetic circuits
MIT	Thomas F. Knight	Amorphous computing

Full Speed Ahead

Even as his lab—and his field—takes its first steps, Knight is looking to the future. He says he isn't concerned about the ridiculously slow speed of today's genetic approaches to biocomputing. He and other researchers started with DNA-based systems, Knight says, because genetic engineering is relatively well understood. "You start with the easy systems and move to the hard systems."

And there are plenty of biological systems—including systems based on nerve cells, such as our own brains—that operate faster than it's possible to turn genes on and off, Knight says. A neuron can respond to an external stimulus, for example, in a matter of milliseconds. The downside, says Knight, is that some of the faster biological mechanisms aren't currently understood as well as genetic functions are, and so "are substantially more difficult to manipulate and mix and match."

Still, the Molecular Sciences Institute's Brent believes that today's DNA-based biocomputer prototypes are steppingstones to computers based on neurochemistry. "Thirty years from now we will be using our knowledge of developmental neurobiology to grow appropriate circuits that will be made out of nerve cells and will process information like crazy," Brent predicts. Meanwhile, pioneers like Knight, Collins, Gardner and Elowitz will continue to produce new devices unlike anything that ever came out of a microprocessor factory, and to lay the foundations for a new era of computing. ◊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Don't expect a DNA-based PC anytime soon. But you might well see even stranger things—including DNA that computes and assembles nanostructures at the same time.

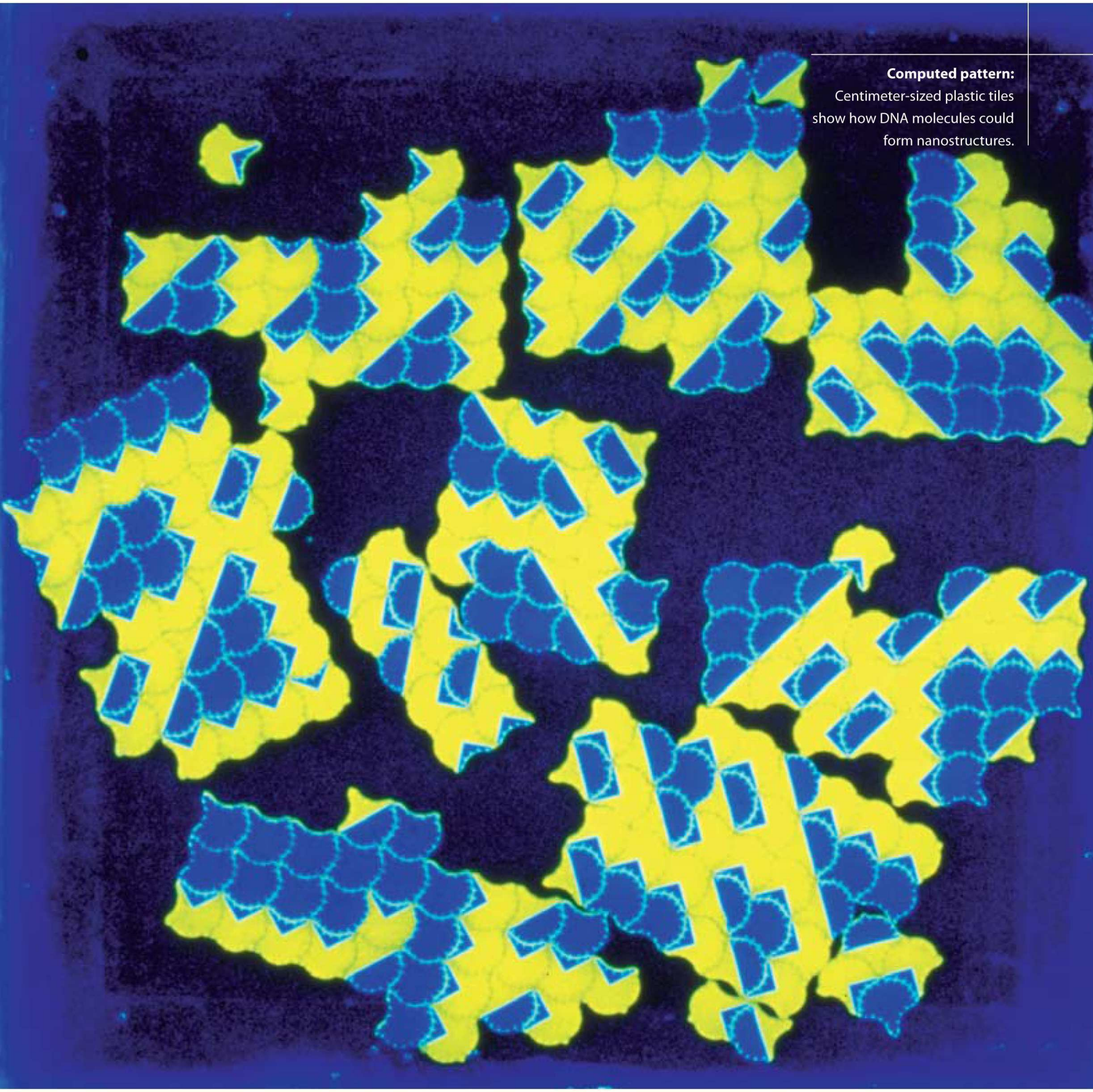
BY ANTONIO REGALADO

DNA Computing

LEONARD ADLEMAN SENDS HIS REGRETS. IN AN E-MAIL FAQ HE uses to fend off journalists seeking interviews, the University of Southern California computer scientist and world-famous cryptographer who invented the field of DNA computing confesses that "DNA computers are unlikely to become stand-alone competitors for electronic computers." He continues, somewhat apologetically: "We simply cannot, at this time, control molecules with the deftness that electrical engineers and physicists control electrons."

It was in 1994 that Adleman first used DNA, the molecule that our genes are made of, to solve a simple version of the "traveling salesman" problem. In this classic conundrum, the task is to find the most efficient path through several cities—given enough cities, the problem can challenge even a supercomputer. Adleman demonstrated that the billions of molecules in a drop of DNA contained raw computational power that might—just might—overwhelm silicon. But since then, scientists have run into tough practical and theoretical barriers. As Adleman and others in the field have come to realize, there may never be a computer made from DNA that directly rivals today's silicon-based microelectronics.

But that doesn't mean they've given up. Far from it. Although computer scientists haven't found a clear path from the test tube to the desktop, what they have found amazes and inspires them. Digital memory in the form of DNA and proteins. Exquisitely efficient editing machines that navigate through the cell, cutting and pasting molecular data into the stuff of life. What's more, nature packs all this molecu-



Computed pattern: Centimeter-sized plastic tiles show how DNA molecules could form nanostructures.

IMAGE: PAUL W.K. ROTHEMUND/PNAS

lar hi-fi equipment into a bacterium not much bigger than a single transistor. Viewed through the eyes of computer scientists, evolution has produced the smallest, most efficient computers in the world—and the beige-box set is hooked.

As Adleman now sees it, DNA computing is a field that's less about beating silicon than about surprising new combinations of biology and computer science that are pushing the limits in both fields—sometimes in unexpected directions. Scientists are still working hard on ways to tap the awesome number-crunching abilities of DNA for specialized types of applications, such as code breaking. But beyond that, the innate intelligence built into DNA molecules could help fabricate tiny, complex structures—in essence using computer logic not to crunch numbers but to build things.

Among the most promising of these new approaches are smart "DNA tiles" invented by Erik Winfree, a 30-year-old computer scientist at California Institute of Technology *("100 Young Innovators,"* TR *November/December 1999).* Winfree's brainstorm is to create nanoscopic building blocks out of DNA that not only can store data but are designed—Winfree likes to say "programmed"—to carry out mathematical operations by fitting together in specific ways. Normally, DNA exists as two intertwined strands of the chemical letters A, G, C and T—the familiar double helix. But Winfree's DNA tiles are made by knotting together three or more of these strands, forming "tiles" about 15 nanometers (billionths of a meter) on their longest side. Taking advantage of DNA's ability to

selectively recognize other strands of DNA, Winfree has "coded" the edges of these tiles so that they come together in just the right way to form tiny built-to-order structures.

In fact, programming DNA in this way could give chemists the kind of deft control "that may allow them to build more complex structures than any considered so far," says Paul Rothemund, a doctoral student in Adleman's USC lab.

to add or multiply numbers. In fact, they showed that with the right set of these hypothetical constructs you could, in theory, do anything an electronic computer can—from playing chess to counting sheep. Winfree's big idea was a simple synthesis: use Seeman's DNA molecules as tiny real-life Wang tiles.

Applied to DNA computing, the strategy could sidestep one of the fundamental problems that has bedeviled the field from the beginning—too much lab work. While DNA computing is good at producing a vast number of answers quickly, things slow down when it comes to picking the right answers out of the mix. Take the traveling salesman problem originally solved by Adleman, in which the object is to find the most efficient route through seven cities connected by 14 one-way flights. Adleman created strands of DNA to represent each flight, then combined them in a test tube to generate every possible route.

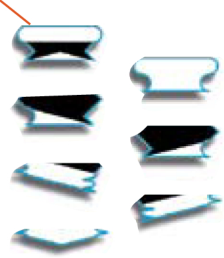
DNA Dominoes

The idea of smart DNA tiles got its start five years ago at Caltech's Red Door café, when Winfree and Rothemund met to discuss Adleman's first DNA computing paper. The publication had set imaginations blazing throughout the world and across scientific disciplines. Were there other ways to compute with DNA? Could it beat silicon? Rothemund brought along a stack of papers showing "all the weirdest things that had been done with DNA." One of these was by Nadrian Seeman, a chemist at New York University who had created cubes, rings, octahedrons and other unlikely shapes from the DNA double helix. Winfree, who was working on a PhD related to artificial learning in robots, immediately saw a way that Seeman's strange versions of DNA could be used to compute.

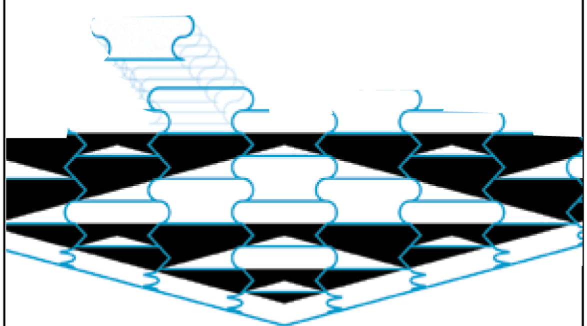
Winfree's intellectual breakthrough was inspired by the theory of Wang tiles—a bit of recondite mathematics related to the patterns that can be created using squares with numbered sides. Like dominoes, the numbers on each Wang tile determine which other tiles it is allowed to touch. By carefully establishing these "matching rules," complex and interesting patterns can emerge as more tiles are added. But it's more than just a game of mathematical dominoes. Because Wang tiles carry both data (the numbers) and simple rules for combining it, mathematicians in the 1960s proved that the tiles could be used

Programmed Nanoconstruction

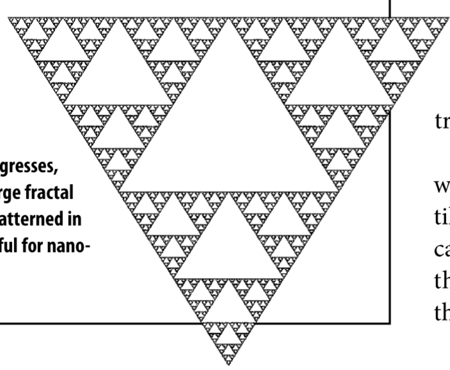
1. A DNA tile is built from four interconnected strands of DNA. It has "sticky ends" that allow it to attach only to DNA tiles with complementary sticky ends.



2. In a conceptual model, a total of 7 tile types are sufficient to build a complex fractal known as the Sierpinski triangle. Matching rules govern how the tiles fit together. Black connects with black, and white with white.



3. The model illustrates how when the DNA tiles are placed together in a test tube they can begin to "self-assemble" according to the matching rules programmed into their sticky ends.



4. As the reaction progresses, the tiles produce a large fractal structure. DNA tiles patterned in this way could be useful for nanotechnology.

BETSY HAYES; SOURCE: ERIK WINFREE/CALTECH

Although the DNA in one-fiftieth of a teaspoon produced 100 trillion answers in less than one second, most of those answers were repeats—and most of them were incorrect. So Adleman's next task was to discard the wrong answers, something that could be done in a jiffy on a PC, but in Adleman's case required several dozen manual laboratory procedures. And that's where the trouble lies with most DNA computing schemes—each "operation" on the data means another time-consuming lab step.

The DNA tiles could solve that problem. Unlike the DNA used by Adleman in his original experiments that combined randomly, Winfree's tiles follow simple rules to get the correct result. "Ideally, you just put [the tiles] in the test tube and whammo!, you've got a right answer," says John Reif, a Duke University computer scientist.

Working with Winfree and Thom LaBean, a biochemist at Duke, Reif hopes to put the idea into practice by creating a simple molecular abacus out of DNA tiles. The goal is to add up binary numbers from zero to eight. With genetic letters standing in for 0s and 1s, the team has designed sets of tiles, each of which represents a possible column in an addition. Rules for combining columns correctly are coded into loose strands of DNA protruding from the sides of the tiles.

If all goes well, the experiment will generate several trillion multi-tile structures each of which has carried out an orderly addition of three binary bits. The scientists then will read off the results using

standard methods for decoding DNA. The experiment underlines the potential power of DNA computers—massive parallelism and speed. Reif estimates that a single test tube of DNA tiles could perform about 10 trillion additions per second—about a million times faster than an electronic computer.

Nanotech C++

THE ENORMOUS RAW POWER OF DNA computing keeps the field moving in spite of all the daunting technical obstacles. Yet even if those obstacles ultimately prove insurmountable, Winfree's work could mean a breakthrough in the construction of ultrasmall devices. Indeed, Winfree himself thinks DNA tiles' most exciting application is as intelligent building blocks that put themselves together piece by piece on the nanometer scale—assembling into large and complex structures *(see illustration, p. 82)*.

Collaborating with Rothemund and Adleman at USC, Winfree aims to fabricate a two-dimensional shape known as the Sierpinski triangle. Named after the Polish mathematician who discovered it in 1915, the triangle is a complex and beautiful fractal produced by repeating a simple geometric rule. The team plans to construct a real-world version of the triangle in a test tube using only seven different DNA tiles. Winfree has designed each tile type to carry out a simple program—to add itself to the growing shape or not, depending on the molecular cues provided by the triangle's outer edge.

In the hands of nanofabrication experts like NYU's Seeman, the DNA tiles could lead to easier methods to make exotic molecular structures—doing for nanotech what CAD and pre-fab building materials have done for the construction industry. "Greater control leads to things that you almost can't imagine," says Seeman. "Our expectation is that this approach can be applied to making designer materials and interesting patterns much more economically."

Seeman's lab, for instance, is already trying to attach nanoparticles of gold to DNA tiles in order to prototype tiny electrical circuits. These DNA "assemblies" would be about 10 times smaller than the tiniest features etched in silicon chips. However, Rothemund notes that there are limits to the patterns "computable" with DNA tiles. "We can't make anything we want," says Rothemund. "But the simple assemblies we've made so far show how well the basic operations work."

They also show how much scientists still have to learn. Winfree compares his efforts so far to one-line programs written in biochemical Basic. What he'd really like to be doing is programming biochemical reactions in C++. He expects this more advanced language will evolve as researchers master new operations, such as selectively removing tiles from an assembly. Winfree speculates that one day it may be possible to bring this growing repertoire of programmable components together to build synthetic systems—call them "nanorobots" if you wish—capable of independently carrying out useful tasks. "The really interesting direction DNA computing is taking us is to see just how far we can learn to program biochemical reactions," says Winfree.

That may sound like futuristic hype, but researchers are already beginning to figure out ways to do it. At Lucent Technologies' Bell Labs, physicist Bernie Yurke, for one, is working with DNA in the hopes of assembling ultrasmall molecular motors. Yurke imagines that some day it might be possible to build a DNA motor that could walk across Winfree's DNA tiling constructs, making chemical changes at specific points. "You could lay down an arbitrarily complex pattern," Yurke says, which might then be transferred to a silicon substrate to fabricate nanometer-scale circuits and transistors. "My hope is that in the future complicated electronic structures like computers will be made this way."

Electronic computers assembled using DNA that computes? It may sound like an unlikely twist in the evolution of DNA computing, but it's one that Adleman believes is entirely in keeping with the field he helped launch. "Like quantum computing, DNA computing is very futuristic, and both make the point that computation doesn't have to take place in the box that sits on our desks," says Adleman, this time in a telephone interview. "Even if they don't become a viable means of computing in the future—and I don't know if they will—we may learn what the real computer of the future should look like." ◊

A single test tube of DNA tiles could perform about 10 trillion additions per second—about a million times faster than an electronic computer.

Computing (and Constructing) With DNA

ORGANIZATION	KEY RESEARCHERS	FOCUS
Bell Labs	Bernie Yurke, Allan Mills	Fabricating DNA motors for assembling electronic components
Duke University/Caltech	John Reif, Thomas LaBean, Erik Winfree (Caltech)	Working on massively parallel addition using DNA tiles
New York University	Nadrian Seeman	Assembling complex nanostructures out of DNA
Princeton University	Laura Landweber, Richard Lipton	RNA-based computer used to solve chess puzzle known as the "knight problem"
University of Southern California	Leonard Adleman	Automating a self-contained lab system for DNA computing; proved, in theory, that DNA can crack DES data encryption standard
University of Wisconsin	Robert M. Corn, Lloyd M. Smith, Anne E. Condon, Max G. Lagally	Adapting DNA-chip technology to do DNA computation on a solid surface


Damn the tuxedos, full speed ahead.

Alternatives to silicon-based computing are long shots. Knowing that, why do HP, Lucent and IBM spend time and money pursuing them? Their reasons may surprise you.

The Corporate Logic

BY ROBERT BUDERI

AN ELBOW-TO-ELBOW CROWD SWARMED INTO THE BELL LABS auditorium on the western border of Greenwich Village on June 30, 1948. Onstage before the guests and reporters stood bow-tied research director Ralph Bown—the small sign at his feet telling the story in a nutshell: "The TRANSISTOR." The Bell Labs folks would soon launch into full-scale demonstrations of the revolutionary device, invented the previous December. But Bown spoke first about how AT&T had engineered its achievement.

"What we have to show you today represents a fine example of teamwork, of brilliant individual contributions and of the value of basic research in an industrial framework," Bown proclaimed.

It should have been a great moment for Bell Labs. After all, technology revolutions don't happen every day. But from a bottom-line point of view, AT&T's transistor breakthrough was less than transformative. That's because when all was said and done, it's doubtful Ma Bell netted a dime from its invention. Instead, the real winners were the specialized firms with better business plans and focus—names like Texas Instruments and Fairchild Semiconductor—who won the race to ready the transistor for mass production and distribution.

Granted, the transistor might seem to be a special case, since as part of an antitrust consent decree AT&T was forced to sell rights to the invention for a modest fee. But to students of the role of science in industrial research, the outcome is all too typical. In fact, for reasons that include corporations' inability to embrace radical change and a lack of commercial applications, a number of other profound discoveries have failed to produce big returns on

PHOTO-ILLUSTRATION BY JOHN WEBER

investments. The list includes semiconductor lasers (GE and IBM), cosmic background radiation (Bell Labs), the scanning tunneling microscope (IBM) and even semiconductor and superconductor tunneling phenomena (Sony and GE); the last three won Nobel Prizes.

From the perspective of corporations that sponsor the research the lesson is clear: Breakthroughs are hard to come by, and the financial payoffs have a troubling tendency to go to someone other than the originator.

This provides some food for thought about today's fervent race to push computing beyond silicon. The field is already littered with failures—think gallium arsenide and optical computers—and current contenders include blue-sky propositions ranging from biological systems to quantum computing. This sort of research fits well in an academic environment, where making money is secondary to the advancement of scientific knowledge (at least in theory), yet much of it takes place in industrial labs. So, since history tells us that the chance of a big payday is remote, why do these companies bother?

The answer is that there are many "hidden" benefits to engaging in basic science—from creating a climate of discovery to staying in touch with the cutting edge. Indeed, the extras are so compelling that the firms bankrolling these studies often don't expect their researchers to produce much of direct market value. "Why is any curiosity-driven research supported in industrial labs?" former IBM vice president for science and technology John A. Armstrong once asked. "There are several reasons, but they do not include the expectation that out of the company's own 'scientific left field,' so to speak, will come new insights or inventions that will radically alter the nature of the company's business."

IF ARMSTRONG'S STATEMENT APPEARS TO run counter to the popular notion that far-sighted corporations invest in basic science to plant the seeds of future growth, it shouldn't. The two views actually complement each other. For one thing, betting on basic research does sometimes pay off financially: DuPont's fundamental polymer studies led to the invention of nylon, and Irving Langmuir's Nobel Prize-winning surface chemistry investigations enabled GE to build a revolutionary light bulb.

Yet by its very nature, most exploratory work fails. What's more, scientific leadership has never been a prerequisite of marketplace triumphs. Witness Japan's dominance in steel, autos, consumer electronics and semiconductor memories—or the rise of Dell, Compaq and Gateway in personal computers.

These truths have led many, Intel cofounder Gordon Moore among them, to conclude that wide-ranging basic research

simply isn't worth it. Moore, formulator of the "law" that has long governed semiconductor manufacturing (see "The End of Moore's Law?" p. 42), points to IBM's Nobel Prize-winning invention of the scanning tunneling microscope (STM)—which does not fit into any of the company's business lines—as a case in point. The STM "is really a great tool," he says, "but IBM is not going to get anything out of it." Moore stresses that society benefits tremendously from basic research—and that Uncle Sam should support it vigorously. But don't expect Intel to dive into the realm of biological processing or quantum computing anytime soon.

Still, not every company shares Intel's philosophy. IBM, Hewlett-Packard, AT&T, Lucent-Bell Labs, NEC and Hitachi are among those supporting world-class investigations into quantum systems, carbon nanotubes, biological processing, molecular computing or other alternative means of data crunching.

This work is so important to IBM that it went gangbusters to nab quantum hotshot Isaac Chuang two years ago (see "Quantum Computing," p. 60), beating out a pack of university and corporate rivals with the lure of a generous salary and state-of-the-art equipment.

Similarly, when HP decided to spin off its measurement and equipment business—now Agilent Technologies—management originally leaned toward placing chemist R. Stanley Williams with the new company. But Williams, whose recent advances in molecular computing received international attention (see Q&A, TR November/December 1999), apparently proved such a hot commodity that he was kept in the HP fold.

All of which underscores the fact that there is more to corporate science than just science. The more subtle payoffs include:

■ **Covering the corporate backside.** While it is relatively easy for research managers to focus R&D on areas likely to affect their firm's interests, it is much harder to be sure nothing has been overlooked. Small but well-considered basic research projects can keep a company's hand in the bigger game in case that something else turns up. As HP chief executive Carly Fiorina says about the necessity of pursuing alternatives to silicon: "You've got to start now or risk being left behind or missing out altogether." (See "Wake-up Call for HP," p. 94.)

■ **Building ties to university science** so that companies are able to understand and exploit what comes out of academic labs. Retired NEC research executive Michiyuki "Mickey" Uenohara, who led his company's vast expansion into basic science in the late 1980s, says it's true that universities should be the center of basic studies. "However," he notes, "it does not excuse industry from performing basic research. We have to have excellent basic research, otherwise we cannot fully utilize university's basic research."

■ **Creating a "culture of research,"** to use the words of Bell Labs vice president of research Bill Brinkman, that will attract top scientists. Hiring the scientific elite raises the cachet and standards of the operation—and in turn brings in more recruits. For example, it was the Bell Labs culture that enticed highly recruited physical chemist Lisa Dhar, who joined the enterprise five years ago after finishing her doctorate at MIT. "Having that mix of long-term and applied research is a very compelling aspect of Bell Labs," she notes. "And that drew me in."

■ **Getting a fundamental perspective** on commercial problems. Locating defects on an integrated circuit holding 200 million transistors, for example, is an immense problem. IBM physicists Jeffrey Kash and James Tsang were studying some exotic aspects of the optical spectroscopy of semiconductors when they realized that the infrared light transistors emit as they switch could overcome this obstacle. Their Picosecond Imaging Circuit Analyzer (PICA) tool now tracks these emissions over intervals of one-trillionth of a second—a far better solution than the Band-Aid approaches often forced on manufacturing engineers. "You can see every transistor light up as it switches," says Tom Theis, director of physical sciences at IBM's Thomas J. Watson Laboratory in Yorktown Heights, N.Y. "So if one is slow because of a defect, you'll find exactly that device." Last November, IBM licensed PICA to semiconductor test and measurement provider Schlumberger.

■ **Public relations.** AT&T may not have made money off the transistor. But the PR impact of its six Nobel Prizes (11 prize winners) and litany of important patents is priceless. Chairman and chief executive Rich McGinn recognized this when Lucent spun off from AT&T in 1996. He placed his headquarters inside Bell Labs and brought the famous research facility into the corporate logo: "Lucent Technologies. Bell Labs Innovations."

BEYOND ALL THESE FACTORS IS ONE critical point: Although places like Bell Labs, IBM and GE became famous for their basic research, science alone did not make them great. Instead, it was their ability to bring together a wealth of talents and viewpoints—scientists with engineers, chemists with mathematicians, deep thinkers with the practical-minded. And from that volatile combination—rather than from basic research itself—leaps the spark of discovery.

Bell Labs' Lisa Dhar experienced the power of such combinations firsthand a few years ago, when she began studying optical holography. This field, which seeks to use light to store data, has long promised unrivaled storage capacity, but it has lacked a good recording medium. Dhar was part of a team of engineers, mathematicians, optical experts, chemists and engineers that not only fashioned a new polymer storage material, but also created a working prototype of a high-density recording system. "There was this incredible feedback that would go on that really accelerated the progress," she recalls. Late last year, Lucent signed an agreement with 3M spin-off Imation to try and develop a product with 25 to 100 times the capacity of today's DVDs—and may even launch a startup of its own to sell the technology.

Viewed in the light of these experiences, it often makes perfect sense for a firm to participate in far-out ventures like quantum or molecular computing that may never provide their own revenue streams. Not only does it provide a lot of buzz, the work helps attract good people, and researchers probably learn some math, chemistry or atomic physics that can be applied to more practical problems.

Top companies know this and often insist on the full package in research, including some blue-sky studies. These efforts never represent a very large fraction of the company's overall R&D budget—and they may never yield a Nobel Prize. But even without a scientific breakthrough, the payoffs can be incalculable. ◊

Portions of this article were adapted from TR *contributor Robert Buderi's new book about corporate research,* Engines of Tomorrow.

Beyond SILICON 2000

Wednesday, June 14
John F. Kennedy Library and Museum
Boston

The United States is currently experiencing the longest economic boom in its history, fueled by a remarkable combination of steady growth and low inflation. The circumstances are so unusually favorable that many economists believe the nation is undergoing fundamental change, and the single most important factor driving that change—these economists say—is the relentless rise in computer power. If Moore's Law—that the power of microchips will roughly double every eighteen months—continues to hold, the country may have not only better living standards for decades to come, it may also postpone the Social Security crisis until the twenty-second century.

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- **Can silicon continue** to increase and sustain the acceleration of computer speed?
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- **Are there limits** to how small and how fast computers can become, and when will those limits be reached?

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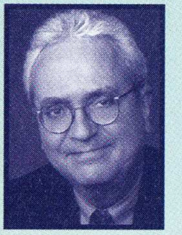
JACK SMITH, Correspondent, ABC News

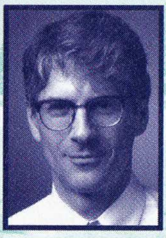
An award-winning ABC News correspondent, Jack Smith contributes to *World News Tonight with Peter Jennings* and to other ABC News programs. For nine years, Smith was the principal correspondent for *This Week with David Brinkley*, filing background reports on the collapse of communism, the Iran-Contra affair and two presidential elections.



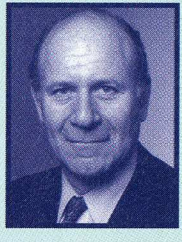
Speakers

JOHN BENDITT, Editor in Chief, *Technology Review*

Mr. Benditt joined *Technology Review* following a nationwide search for a dynamic new editor in chief. From 1993 to 1995, Mr. Benditt served as features editor for *Science Magazine*, where he subsequently served as editor of the new online publication for young scientists, *Next Wave*. During his tenure at *Scientific American*, Mr. Benditt had the distinction of planning, commissioning and editing ten major articles for the magazine's single-topic issue devoted to AIDS.

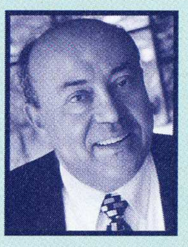


JOEL S. BIRNBAUM, Chief Scientist, Hewlett-Packard



From 1991 to February 1999, Dr. Birnbaum served as Hewlett-Packard's senior vice president for research and development and as director of HP Labs—the company's central research and development organization. Today, Dr. Birnbaum reports to Hewlett-Packard's chairman and CEO in the role of chief scientist, helping to shape the company's overall technology strategy.

ANDREW J. VITERBI, Founder, QUALCOMM



Dr. Viterbi, one of the founders of QUALCOMM, has served as vice chairman of the QUALCOMM board of directors since the company's inception in 1985 and as chief technology officer from 1985 to 1996. Dr. Viterbi received his BS and MS degrees in electrical engineering from MIT and his PhD in the same field from the University of Southern California. He is a member of the National Academy of Engineering and the National Academy of Sciences.

SOPHIE VANDEBROEK, Director, Xerox Research Center of Canada

Dr. Vandebroek is the director of the Xerox Research Center of Canada, and she manages the Xerox Technology Program Office. She earned her MS degree in electro-mechanical engineering from the Katholieke Universiteit, Leuven, Belgium, and a PhD in electrical engineering from Cornell. Vandebroek also conducted research at the IBM's T.J. Watson Research Center, at Belgium's Interuniversity Microelectronics Center; and at HP Labs in Palo Alto.

Hotel Accommodations

Hilton Boston Logan Airport

The new Hilton Boston Logan Airport is the official conference hotel for Beyond SILICON 2000. Attendees should contact the hotel directly at 1-800-HILTONS or 617-568-6700, extension 5900.

Attendees are eligible for a discount rate of $159 for single- and $184 for double-occupancy rooms.

Partial list as of April 1. Please visit our web site at www.techreview.com/beyondsilicon for updated information.

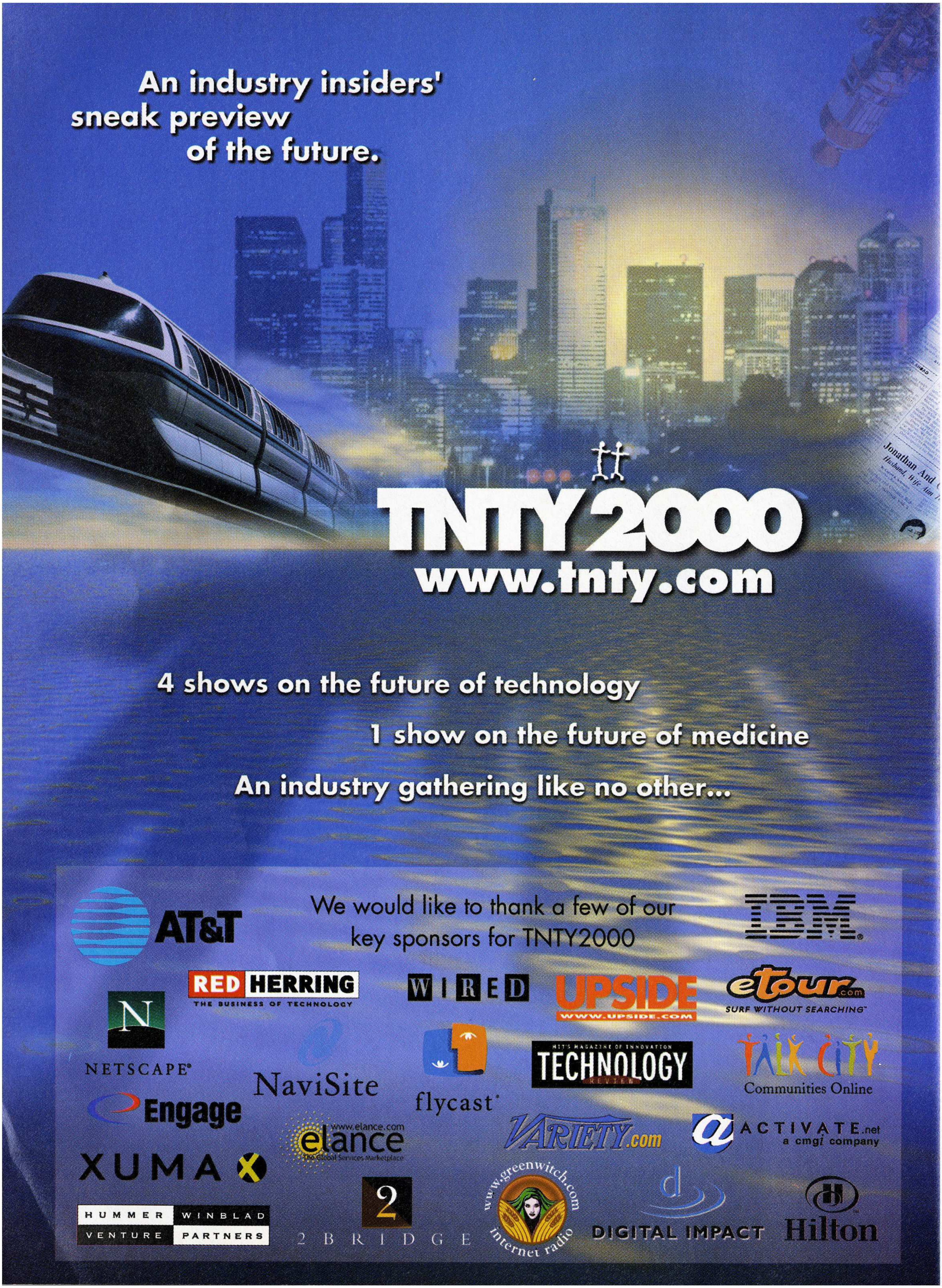
She's baaaack. Carly Fiorina, a former Hewlett-Packard temp, has returned to jolt the information technology giant out of its lethargy. Her goal is simple: Make the company "unbeatable" in the coming age of pervasive computing.

Wake-up Call for HP

Q & A

BACK WHEN SHE WAS A STANFORD University undergrad, Hewlett-Packard president and chief executive officer Carleton "Carly" Fiorina worked as an HP temp shipping clerk. After graduation, she quickly moved on to bigger and better things, rising from AT&T account rep to lead Lucent Technologies' spinoff from the Bell mother ship. Her subsequent success as head of Lucent's Global Service Provider Business helped enable Fiorina to beat out a strong pack of rivals to win the top HP spot a year ago.

Fiorina returned to Silicon Valley to take the reins of a company bedeviled by inconsistent financial performance. Seeking to reinvent HP, she evoked its original "garage" spirit and launched a $200 million brand and advertising campaign that included a new logo emblazoned with the word "invent." She also cast aside HP's recent division into four semi-autonomous business enterprises, each with its own president and CEO, in favor of a more cohesive structure with one chief executive: Carly Fiorina.



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Reminding us that Bill Hewlett and Dave Packard "didn't operate a democracy and they made very fast decisions," Fiorina has mandated aggressive goals: growth in revenues *and* earnings of 12 to 15 percent for the fiscal year that began last November 1. She's off to a pretty good start. The typically slow first quarter that ended on January 31—the first totally on her watch—saw revenues up 14 percent, though profits had farther to go. Meanwhile, HP's stock price, at $114.65 when she took over, hit $155.55 earlier this year, and was trading at around $147 when *TR* went to press.

Her early success, seemingly boundless energy and fearless leadership have already made Fiorina an American business legend. She spoke with *TR* contributing writer Robert Buderi about what it takes to reinvent a major corporation, and what Hewlett-Packard sees as the future of computing.

TR: What did you see in HP that made you excited to come back—and what are the main things you didn't see that you felt needed to be done or put in place?
FIORINA: I could see that HP was at a pivotal point. It's a unique company at a unique time in its history, a company poised to take full advantage of the Internet Age. I want to help the company achieve the right balance between preserving the core values of HP, the soul of the place that has been so special and so revered, but at the same time, reinvent the business in important ways.

TR: Can you describe the key steps to reinventing the company in more detail?
FIORINA: Reinvention to me is about four things. It's about culture, it's about strategy, it's about what you measure and how you reward those measurements, and it's about business process. All of those levers need to be pulled.

At a cultural level, we have to be explicit about the values and the behaviors that help us, and explicit about the behaviors that are getting in our way. So our emphasis on reaffirming the core values that have been with this company for 60 years—trust, integrity, teamwork, contribution—is a reaffirmation of the behavior we need to carry us forward.

Reinvention also requires some tough strategic choices about how and where we want to play. Those choices are particularly difficult for a company with the depth and breadth of capability of HP, because a company like HP honestly can do anything it wants to do. And so the hardest strategy is deciding what *not* to do. I'll give you a very simple example. We had inside the company when I arrived at least five separate architectures for e-publishing—all of them good. And what we had to do was decide we're going to have one—so that we have sufficient focus on that one platform to make sure it really is a winning play.

Metrics has a lot to do with what's expected. So we talk around minimally acceptable performance and aspirational performance. Minimally acceptable performance is performance that meets the expectations of customers and shareowners. And aspirational performance is performance that leads the market—that sets the standard—and we pay people very differently for those two levels of performance.

Then there's a whole very broad area around processes—whether we're talking about a pricing process (or) the processes we use to build the relationship between our employees and the company.

TR: Going back to the point about culture, the traditional HP culture is one of excellence in engineering and conservative management. This has many positive aspects. But it has also made it extremely difficult to take risks.
FIORINA: You are right that HP had become too reluctant to take risks. We'd become too slow. Everything had to be decided by consensus. But bad habits develop in any company, any family, any individual. So I've asked the company's senior leadership, management ranks—indeed all employees—to "look in the mirror." In other words, to be explicit and open about what has to change, what should stay the same. I intend to preserve and nurture the core values that have made this company great. Respect and service to customers and to the communities in which we live and work are things I call HP's shining soul. It's our essence, giving us a competitive advantage.

TR: How does this relate to your $200 million brand campaign?
FIORINA: The brand is a promise to our customers and our partners about who we are, where we've been, and where we intend to go. It's a reminder to the people of HP about our inventive capability, returning, in a way, to the "Rules of the Garage"—reflecting the garage in which HP was born. You'll see it in ads, in poster form in employees' cubicles, and it's actually become a popular item among our customers, too. So, we are building very consciously an organization where roles and responsibilities are clear, but where there also is a requirement for interdependence and collaboration—and we're doing that because we think the market demands it. We're doing it because we believe when we really leverage the capabilities of this company we are, I don't want to sound overly aggressive, but we're almost unbeatable.

TR: Shortly before you joined, HP announced plans to split off its original instrument business—something it's subsequently done as Agilent Technologies. Why was that move necessary? Doesn't it take away a lot that was unique about the company and make innovation more difficult?
FIORINA: Focus is crucial for a company, especially a large one. I believe it was a wise decision to spin off Agilent—making up HP's former test and measurement, medical products, chemical analysis and semiconductor businesses. What continues under the HP name—computers, printing and imaging products, information technology services and software—has a rich history in innovation, outstanding people and technologies, and world-class partnerships. We're confident both companies will be able to innovate better and faster as separate entities. And there's no reason we can't partner on certain things.

TR: Until the 90s, the company had rolled along at something like 19 percent growth per year. More recently, growth has been sluggish at best. In what areas will you push for new growth opportunities?
FIORINA: HP can grow faster as well as earn more; I'm convinced of it. We are now poised to capitalize on some real innovations with huge market potential. Digital imaging is one, e-services is another; at the same time, we have to aggressively continue to defend and grow our core businesses. We will do all of this passionately. And we are growing again. We have become the world's number one consumer IT supplier, and we've just begun.

“Ten years may sound like a lot in ‘Internet time,’ but it’s not in reality—not when you’re talking about replacing a technology like silicon that will reach its physical and financial limits.”

We see great growth opportunities outside the U.S. HP has been a global firm for a very long time. We’ve been in Asia for thirty years; we’ve been in Europe that long. We’ve been in places in Latin America that long. So for us it’s not about building a presence—we have it. We have deep roots in countries where longevity matters. Now it’s a question of leveraging off the relationships and the presence that we have.

TR: Your new logo includes the word “invent.” This is reminiscent of the Lucent motto’s reference to “Bell Labs innovations.” Does this mean a bigger role for HP Labs (the company’s central research house)?

FIORINA: HP Labs has always played a critical role in the company. In fact, the innovation that’s come out of that organization has been one of the best-kept secrets in the industry. We’re changing that by letting the world know what a tremendous asset we have in the Labs. We’re also going to put more of a focus on developing “disruptive technologies”—those that create entirely new markets. We had gotten to the point where HP Labs was really totally funded by the businesses—and that caused a focusing of the Labs’ attention on pretty near-end opportunities. Now, that connection between the Labs and the business is important and we don’t want to sever that connection. But at the same time we also want to give the Labs the resources and the freedom to focus on farther-out technologies—and also to feel free enough from the day-to-day budget battles that they can be a voice of contention where one is necessary. And so what we’ve done now is say there will be a portion of HP Labs’ funding which will be top-down, which will be based upon both further-out technologies and perhaps alternative approaches to a problem.

But you also need to remember, HP was founded by two inventors 60 years ago. We are a company of inventors, so the word “invent” is for every HP employee, not just those at Labs. We can, and do, invent different ways of working and new business models, in addition to new technology.

TR: Can you provide some examples of “disruptive technologies” that you’re working on?

FIORINA: Digital photography is one area. We have some of the world’s best color scientists who have written algorithms for a chip that will go into a digital camera that will virtually guarantee you a perfectly exposed picture every time. Vivid, natural colors, sharp focus and no more images lost in the shadows or bright lights. Our technology is going to revolutionize the world of consumer photography. We’re also doing some ground-breaking work in advanced storage technologies. One, called ARS, or Atomic Resolution Storage, holds the promise of storage densities a thousand times greater than those that exist today. You could carry enough storage in your pocket to record everything you’ve ever seen, done or heard in your entire lifetime. That kind of capacity just changes the ground-rules for what you can do with storage technology.

TR: The pursuit of this kind of storage capacity raises the question of the future of computing, which is the subject of this special issue of *TR*. Where does the company believe computing is heading—over the next few years and farther down the road—and what will HP’s own role be in fulfilling this vision?

FIORINA: Well, we are really playing now at the intersection of three technology vectors—the infrastructure or computing utility, information appliances and e-services. We believe that the vision of pervasive computing—an idea, by the way, that HP Chief Scientist Joel Birnbaum promoted back in the early 90s—is finally going to become a reality. In the next five years, there are going to be 50 million new hand-held computers and a billion cell phones. You’re already seeing a lot of new services popping up to serve this market. Well, that’s just the beginning. When computing becomes truly pervasive, it’s going to change the way we work, play, become educated, get medical treatment, deal with the government—in fact, the way we live our lives.

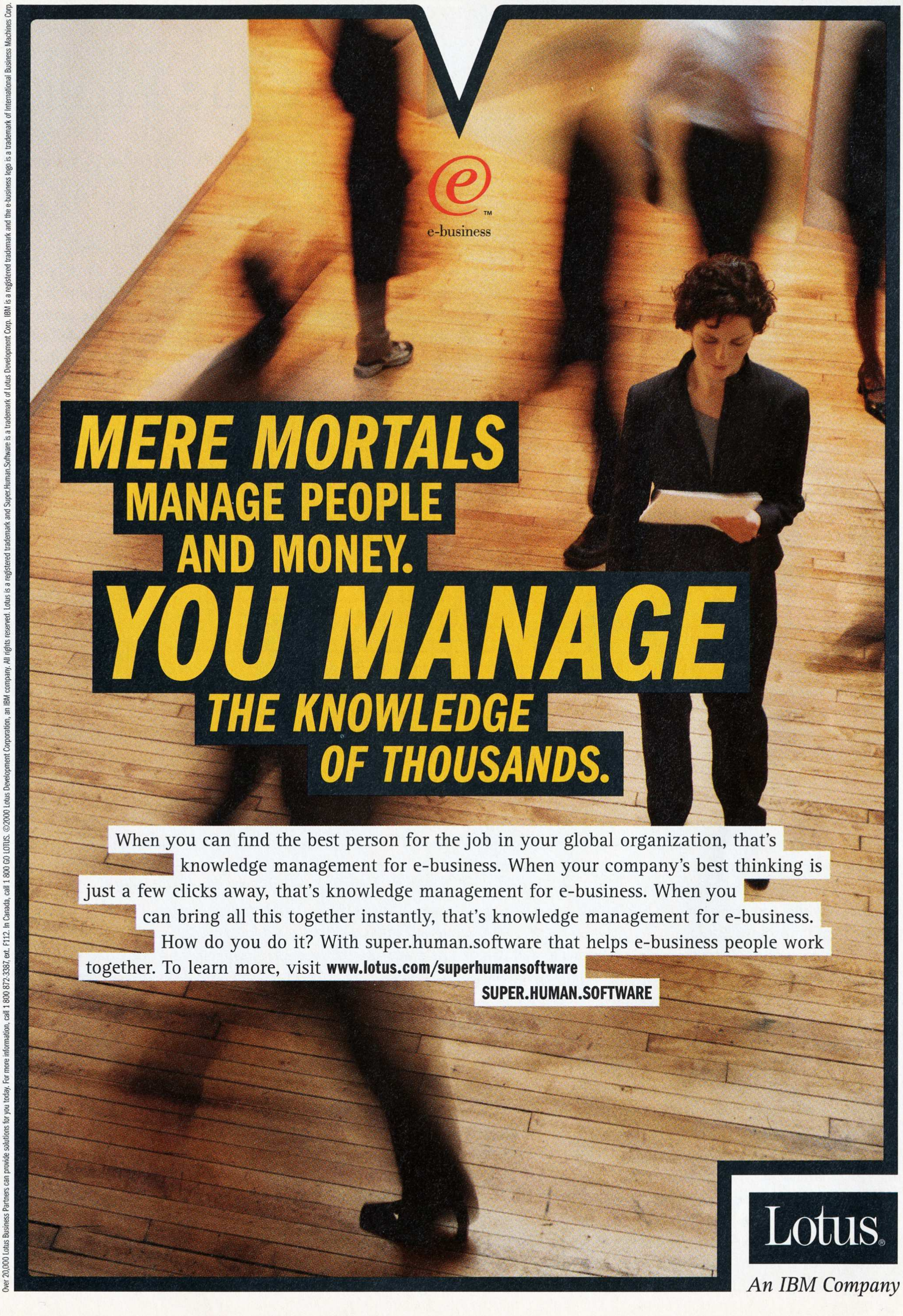
For this to happen, you’re going to need an infrastructure that works, regardless of product, platform or program. And you’re going to need a wide variety of smart information appliances that can be tied together. Once those two vectors are in place, it opens up an absolutely unlimited number of e-service opportunities. At HP Labs, we have a research project called “Cool Town,” which we think provides the practical infrastructure that’s needed. Every person, place and thing in “Cool Town” has a Web presence. They can all be tied together. We’re also working on “context-aware” appliances—tools that know who you are, where you are and what’s going on around you. Imagine a phone that knows—by some biometric means, for example—who you are and uses GPS to determine where you are. It can know all of the numbers you call, your passwords, access codes and so on. All you have to do is say, “Call Bob Buderi,” and it will know exactly how to reach you, whether you’re calling from Palo Alto or Cambridge.

Of course, there’s a tremendous amount of work to do to make this vision a reality. But we’re getting there. And the payoff for HP and its customers is tremendous.

TR: HP scientist Stan Williams is working on basic nanocomputer technologies that may not bear fruit for 10 years or longer. Can a company really afford to support this kind of basic research, given the extreme pressures of the here and now?

FIORINA: We can’t afford not to. Ten years may sound like a lot in “Internet time,” but it’s not in reality—not when you’re talking about something as fundamental as replacing a technology, like silicon, that will finally reach its physical and financial limits. You’ve got to start now or risk being left behind or missing out altogether.

Basically, high-tech companies have to do both: continue their efforts to extend current technologies, and to work on “disruptive” technologies that show great promise for the future. There are very few companies in the world that have the resources to do both successfully. HP is one of them. ◊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Ducking the Virus

I happened to be watching a New York Knicks game on television the other night when the revolving billboard beneath the scorer's table unfurled an advertisement for Propecia, the Merck drug that prevents hair loss. In one of those Proustian leaps of association that often come to me while I'm in couch-potato mode, I found myself thinking about April showers, and mosquitoes, and medicine.The connection may seem circuitous, but hang on—we'll get there.

April showers will bring May mosquitoes in the New York City area, and with them renewed concerns about West Nile fever, the exotic mosquito-borne virus that caused an outbreak of encephalitis in the city last year. The question perplexing many public health officials is this: Will the virus survive the winter in infected mosquitoes, like other mosquito-borne viruses (or arboviruses) in this country? And will it reappear in the city this spring?

West Nile caught everyone by surprise when it made its debut in the Western Hemisphere last summer. The disease was at first misdiagnosed as St. Louis encephalitis. Seven people, all elderly, died of encephalitis, a brain infection; dozens became ill.

As someone who has written about arboviruses for nearly 20 years, I understand that the risk of becoming infected is low, and the risk of developing encephalitis lower still. As a resident of Brooklyn, though, I wasn't exactly thrilled by the helicopters that droned overhead in September, dousing our backyard with malathion. And as the father of an 18-month-old boy, I remember the sudden fear when I went to fetch Sandro one morning from his crib and noticed that he was covered with mosquito bites.

With a lull in the outbreak, we might ask what lessons can be learned from West Nile. One lesson it *doesn't* seem to be imparting is the notion, indirectly suggested last fall, that the outbreak might be human-made. An article in *The New Yorker* last October implied that the CIA was concerned that the rise of West Nile "might have been an act of bioterrorism." But if West Nile were an agent of biowarfare (BW), why use an arbovirus, with a complicated avian transmission cycle, instead of a directly transmissible agent like smallpox? And why would the first cases turn up in a distant corner of Queens rather than, say, Times Square or on Pennsylvania Avenue? "The BW angle is BS," one knowledgeable government source told me.

Rather than a terrorist plot, the unexpected appearance of West Nile has the quality of Mother Nature clearing her throat. West Nile has been very much on the move, spreading from Africa as far east as India and as far west as Romania. Dengue fever and yellow fever, to mention other mosquito-borne diseases, have happily colonized the Western Hemisphere. If the host is mobile, viruses are the ultimate hitchhikers.

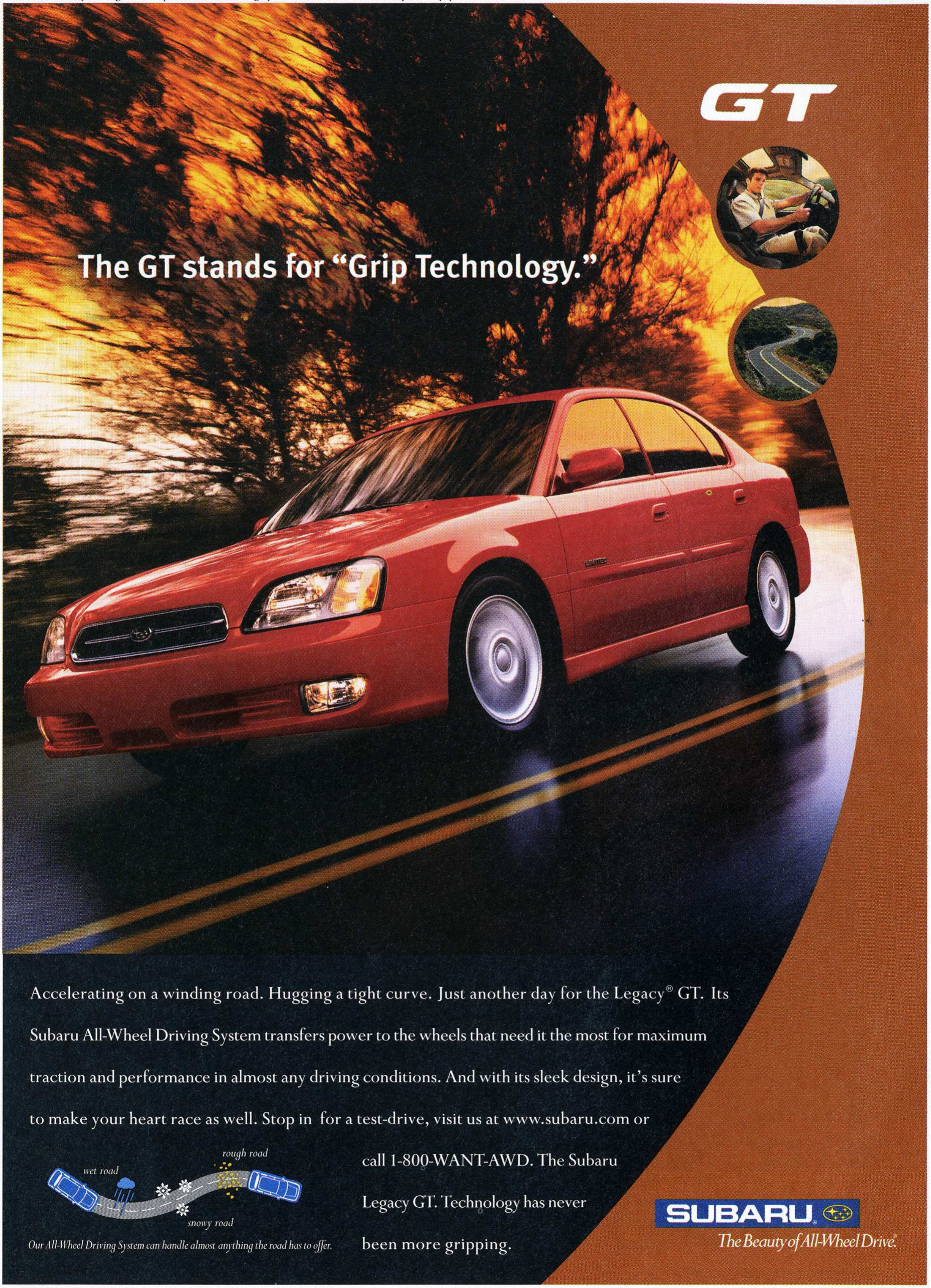
The most important question isn't finding a conspiracy to finger—it's finding out whether we're ready. How prepared will we be if West Nile evolves into something more virulent, or if something much nastier turns up? The major pharmaceutical companies have largely ignored, curtailed or terminated programs to develop drugs against infectious diseases that predominate in the unremunerative, Third World markets where millions perish each year from devastating infectious diseases. True, the Bill and Melinda Gates Foundation has donated $750 million to expand vaccine use in developing countries, and Merck and three other drug companies recently announced plans to donate $100 million worth of vaccines for poor children. But wouldn't it be nice to feel that such magnanimous gestures occurred independent of either federal antitrust lawsuits or growing public discontent over the price of drugs?

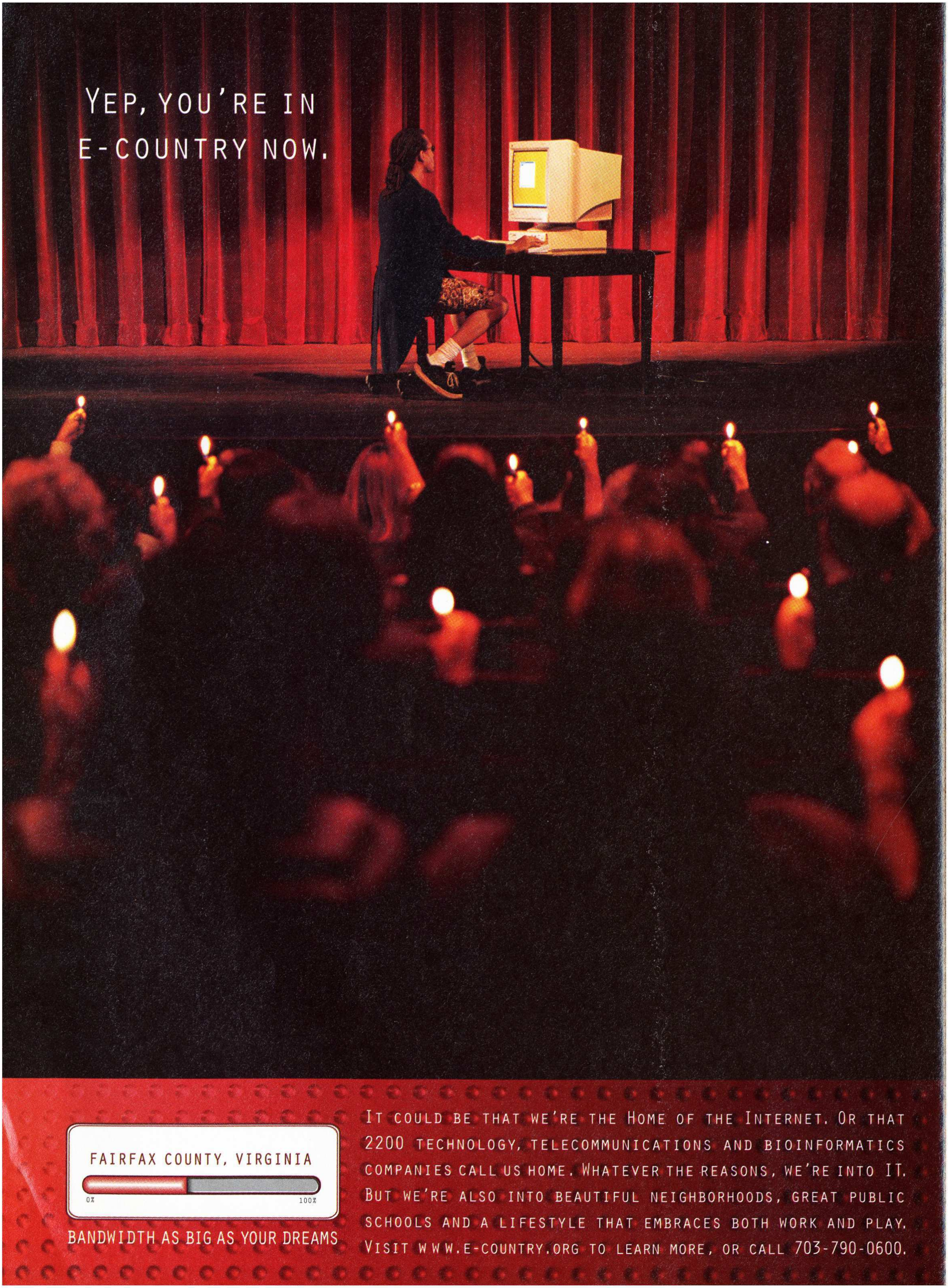
Big Pharma has little interest in curing the infections prevalent in poor countries. That's a problem for us all.

A cynical friend of mine has complained for years that it is in the economic interests of drug companies to avoid finding cures for diseases, because it's bad business. The perfect drug, from their point of view, he argues, is one that never cures the underlying condition and must be taken for a lifetime. I've tried to disabuse him of this view, but when I see "lifestyle" drugs and maintenance therapies relentlessly pitched on TV (and now we're getting back to that Knicks game), it's getting harder to argue the point. The "crown jewel" of Pfizer's recent $90 billion takeover of Warner Lambert was Lipitor, the cholesterol-reducing drug that is anticipated to rack up a staggering $5 billion in sales this year. Given the recent blitz of advertising for Propecia, Viagra and Prozac, you'd think the loftiest goal of biomedical research these days is to make everyone hairy, horny and happy—rather than healthy.

We don't need to vaccinate New Yorkers against West Nile encephalitis—not yet, at least. It's too early in the story, and the numbers are surpassingly small. But the subtext of the West Nile epidemic—indeed, the epidemiological confusion that led to its initial misdiagnosis—is the notion that it can't happen here. Clearly, it can. And just as clearly, there may be other, more infectious and virulent pathogens, seemingly tethered to the poverty and deprivations of the developing world, which could give a new and sickening twist to our embrace of globalization and for which we are unprepared. ◊

The ABC's of Safety: Air bags. Buckle up. Children in back. Legacy GT Limited Sedan shown with optional equipment.

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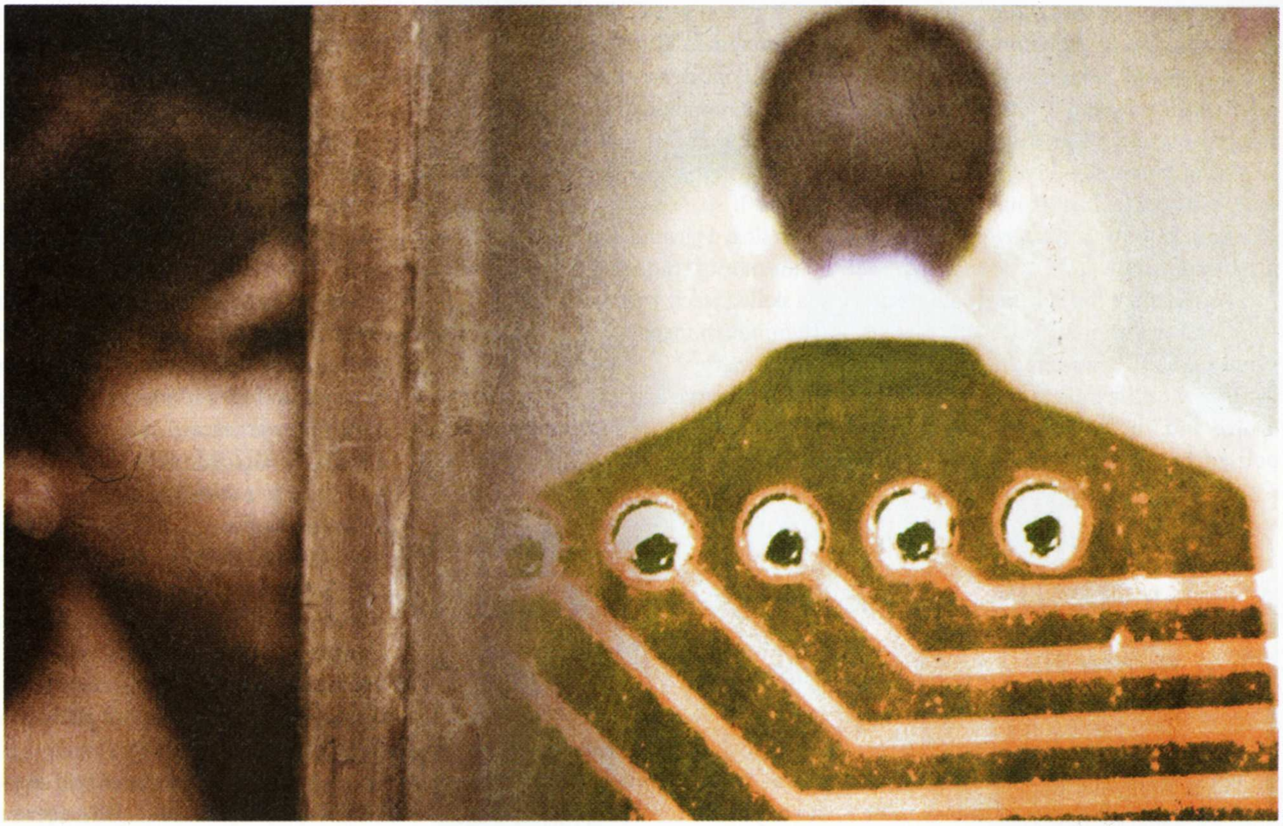


MARC YANKUS

VIEWPOINT | BY STEVEN PINKER

Life in the Fourth Millennium

Science and technology could transform our world—if it weren't for human nature

PEOPLE LIVING AT THE START OF THE third millennium enjoy a world that would have been inconceivable to our ancestors living in the 100 millennia that our species has existed. Ignorance and myth have given way to an extraordinarily detailed understanding of life, matter and the universe. Slavery, despotism, blood feuds and patriarchy have vanished from vast expanses of the planet, driven out by unprecedented concepts of universal human rights and the rule of law. Technology has shrunk the globe and stretched our lives and our minds.

How far can this revolution in the human condition go? Will the world of 3000 be as unthinkable to us today as the world of 2000 would have been to our forebears a millennium ago? Will our descendants live in a wired Age of Aquarius? Will science explain the universe down to the last quark, extinguishing mystery and wonder? Will the Internet turn us into isolates who interact only in virtual reality, doing away with couples, families, communities, cities? Will electronic media transform the arts beyond recognition? Will they transform our minds?

Obviously it would be foolish to predict what life will be like in a thousand years. We laugh at the Victorian experts who predicted that radio and flying machines were impossible. But it is just as foolish to predict that the future will be utterly foreign—we also laugh at the postwar experts who foresaw domed cities, jet-pack commuters and nuclear vacuum cleaners. The future, I suggest, will not be unrecognizably exotic because across all the dizzying changes that shaped the present and will shape the future one element remains constant: human nature.

After decades of viewing the mind as a blank slate upon which the environment writes, cognitive neuroscientists, behavioral geneticists and evolutionary psychologists are discovering instead a richly structured human psyche. Of course, humans are ravenous learners,

but learning is possible only in a brain equipped with circuits that learn in intelligent ways and with emotions that motivate it to learn in useful ways. The mind has a toolbox of concepts for space (millimeters to kilometers), time (tenths of seconds to years), small numbers, billiard-ball causation, living things and other minds. It is powered by emotions about things—curiosity, fear, disgust, beauty—and about people—love, guilt, anger, sympathy, pride, lust. It has instincts to communicate by language, gesture and facial expressions.

We inherited this standard equipment from our evolutionary ancestors, and, I suspect, we will bequeath it to our descendants in the millennia to come. We won't evolve into bulbous-brained, spindly-bodied homunculi because biological evolution is not a force that pushes us to greater intelligence and wisdom; it simply favors variants that out-reproduce their rivals in some environments. Unless people with a particular trait have more babies worldwide for thousands of generations, our biological constitution will not radically change.

It is also far from certain that we will redesign human nature through genetic engineering. People are repulsed by genetically modified soybeans, let alone babies, and the risks and reservations surrounding germ-line engineering of the human brain may consign it to the fate of the nuclear-powered vacuum cleaner.

If human nature does not change, our lives in the new millennium may be more familiar than the futurologists predict. Take education, where many seers predict a revolution that will make the schoolroom obsolete. Some envision Summerhillesque free schools, where children interact in a technology-enriched environment and literacy and knowledge will just blossom, free from the drudgery of drill and practice. Others hope that early stimulation, such as playing Mozart piano concertos to the bellies of pregnant women, will transform a plastic brain into a superlearner.

But an alternative view is that education is the attempt to get minds to do things they are badly designed for. Though children instinctively speak, see, move and use common sense, their minds may be constitutionally ill at ease with many of the fruits of modern civilization: written language, mathematical calculation, the very large and very small spans of time and space that are the subject of history and science. If so, education will always be a tough slog, depending on disciplined work on the part of students and on the insight of a skilled teacher who can stretch stone-age minds to meet the demands of alien subject matter.

Our mental apparatus may also constrain how much we adults *ever* grasp the truths of science. The Big Bang, curved 4-D space-time and particles that act like waves—all are required by our best theories of physics but are incompatible with common sense. Similarly, consciousness and decision-making arise from the electrochemical activity of neural networks in the brain. But how moving molecules should throw off subjective feelings (as opposed to mere intelligent computations) and choices for which we can be held responsible (as opposed to behavior that is caused) remain deep mysteries to our Pleistocene psyches.

Human nature dictates that our future could be much more like the present than many predict. That might be cause for despair—or celebration.

That suggests that our descendants will endlessly ponder the age-old topics of religion and philosophy, which ultimately hinge on concepts of matter and mind. Why does the universe exist, and what brought it into being? What are the rights and responsibilities of living things with different brains, hence different minds, from ours—fetuses, animals, neurologically impaired people, the dying? Abortion, animal rights, the insanity defense and euthanasia will continue to agonize the thoughtful (or be settled by dogma among the unthoughtful) for as long as the human mind confronts them.

One can also predict that the mind will shape, rather than be reshaped by, the information technology of the future. Why have computers recently infiltrated our lives? Because they have been painstakingly crafted to mesh better with the primitive workings of our minds. The graphical user interface (windows, icons, buttons, sliders, mice) and the World Wide Web represent the coercion of machines, not people.

We have jiggered our computers to simulate a world of phantom objects that are alien to the computer's own internal workings (ones, zeroes and logic) but are comfortable for us tool-using, vision-dependent primates. Many other dramatic technological changes will come from getting our machines to adapt to our quirks—understanding our speech, recognizing our faces, carrying out our desires in accord with our common sense—rather than from getting humans to adapt to the ways of machines *(see "Speech and Vision," p. 24)*.

Our emotional repertoire, too, ensures that the world of tomorrow will be a familiar place. Humans are a social species, with intense longings for friends, communities, family and spouses, consummated by face-to-face contact.

E-mail and e-commerce will continue their inroads, of course, but not to the point of making us permanent antisocial shut-ins; only to the point where the increase in convenience is outweighed by a decrease in the pleasure of being with friends, relations and interesting strangers. If our descendants have spaceports and transporter rooms, they will be crammed at Thanksgiving and Christmas.

But human relationships also embrace conflicts of biological interests, which surface in jealousy, sibling rivalry, status-seeking, infidelity and mistrust. The social world is a chess game in which our minds evolved as strategists.

If so, the mental lives of our descendants are not hard to predict. Conflicts with other people, including those they care the most about, will crowd their waking thoughts, keep them up at night, animate their conversation and supply the plots of their fiction, whatever the medium in which they enjoy it.

If constraints on human nature make the future more like the present and past than futurologists predict, should we sink into despair? Many people, seeing the tragedies and frustrations of the world

today, dream of a future without limits, in which our descendants are infinitely good, wise, powerful and omniscient. The suggestion that our future might be constrained by DNA shaped in the savanna and ice ages seems depressing—even dangerous.

Admittedly, many declarations of ineluctable human nature turned out to be wrong and even harmful—for example, the "inevitability" of war, racial segregation and the political inequality of women. But the opposite view, of an infinitely plastic and perfectible mind, has led to horrors of its own: the Soviet "new man," reeducation camps and the unjust blaming of mothers for the disabilities and neuroses of their children.

Many leaps in our quality of life came from the recognition of universal human needs, such as life, liberty and the pursuit of happiness, and of universal limitations on human wisdom and beneficence, which led to our government of laws and not men.

Universal obsessions are also the reason that we enjoy the art and stories of peoples who lived in centuries and millennia past: Shakespeare, the Bible, the love stories and hero myths of countless cultures superficially unlike our own. And the mind's foibles ensure that science will be a perennial source of enchantment even as it dispels one mystery after another. The delights of science—of the Big Bang, the theory of evolution, the unraveling of the genes and the brain—come from the surprise triggered by a conclusion that is indubitably confirmed by experiment and theory but that contradicts standard human intuitions.

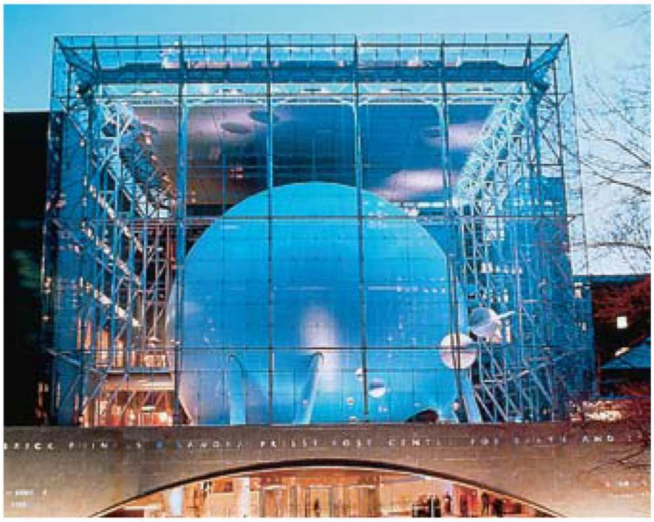
Third-millennium futurologists should realize that their fantasies are scaring people to death. The preposterous world in which we interact only in cyberspace, choose the endings of our novels, merge with our computers and design our children from a catalogue gives people the creeps and turns them off to the genuine promise of technological progress. The constancy of human nature is our reassurance that the world we leave to our descendants will be one in which scientific progress leads to delight rather than boredom, in which our best art and literature continues to be appreciated, and in which technology will enrich rather than dominate human lives. TR

MIXED MEDIA

Digital Deep Space

Ogling the universe in a brand-new, high-tech planetarium

WITH THE VOICE OF actor Tom Hanks as your guide, you are whisked away on a spectacular tour of the cosmos. First a mysterious, Death Star-like sphere rises up from the floor before you. Vivid computer-generated star fields and galaxies glide before you at many times the speed of light. Finally, your seat rumbling beneath you, you experience a flume ride through a Disney-esque black hole.



AMERICAN MUSEUM OF NATURAL HISTORY

The Hayden Space Theater simulates the sky with fiber optics and computers.

Welcome to the 21st-century incarnation of New York's Hayden Planetarium. Housed in the Rose Center for Earth and Space, a recently opened wing of the American Museum of Natural History, it is to a 20th-century planetarium as George Lucas is to Galileo. And while the planetarium's combination of advanced projection systems is now unique, it should soon be replicated in other revamped or new space theaters around the world.

The traditional domed planetarium—using optical projection and gears embodying Copernican astral mechanics—was first demonstrated in 1923 by Zeiss, the German optics company. The original Hayden Planetarium, part of the first wave of sky theaters in the U.S., opened on Manhattan's Upper West Side in 1935. Over the years, generations of children broadened their horizons beneath its virtual planets and stars—heavenly bodies usually unseen in the city. (Among those turned on to the stars here was Bronx-born astrophysicist Neil de Grasse Tyson, now the Hayden's director.) About 100 other major planetariums and more than 1,000 smaller ones have cropped up since, many built at schools and colleges with funding generated by the Space Race of the 1950s and 1960s.

In recent years, though, planetariums have had to compete for the public's attention with theme park rides, Hollywood special effects and high-resolution IMAX movies. The most recent trend in planetarium buildings has been an odd archi-

HYPERFICTION

Tome of The Unknown Authors

It's a literary event, a reading of a collaborative novel. Oddly, one suit-wearing author begins by reading a fictionalized account of arriving today at the reading. The story continues, recounting the authors' drug experiences with local celebrities. Then, someone from the audience yells out "hit the deck"—an underlined phrase in the text being read, up on the screen. (This novel is hypertextual, after all.) The reader clicks there, jumping to a new page. One of his collaborators stands to take his place.

The hypertext novel at the center of this gong show is called *The Unknown*. It can be read, free of charge, at www.soa.uc.edu/user/unknown/ and was written principally by William Gillespie, Scott Rettberg and Dirk Stratton.

The Unknown began when those authors simply sat down and started writing one June day in 1998, in Cincinnati. (Two of them were then graduate students and one was a college writing teacher. At the time, they were, as Rettberg says, completely "unknown" as writers.) They ground out the first 80 pages in a single 36-hour session. After this creative frenzy, they revised, organized and expanded the work; Rettberg figures it now contains about 800

pages. Most importantly, they hyperlinked the pages, offering different reading paths through one central narrative: the wild book tour of a group of successful authors. Since similar book-tour episodes take place in different cities, a reader can jump around without getting too confused.

THE UNKNOWN WEB SITE

Linked work: hyper-authors Stratton, Gillespie and Rettberg.

Originally, the authors wanted to use *The Unknown* to promote a printed book. This so-called *Unknown Anthology* didn't appear, though—it simply became the central conceit of the self-referential *Unknown* hypertext, which itself became an award-winning hit and which they have read/performed at Brown University, Georgia Tech, and other

tectural compromise: a tilted dome with steeply banked audience seating to accommodate both IMAX and star shows. When the Hayden's threadbare facilities were in need of a major refurbishing, the trustees of the Natural History Museum opted for a new architectural metaphor: One of the universe's own spheres, 2 million kilograms of it, housed inside the showcase-like, $210 million Rose Center. At the heart of the sphere is Hayden II's 429-seat Space Theater. It is equipped with the latest Zeiss projector—the Universarium Model IX—which includes a more detailed portrayal of our home galaxy, the Milky Way, as well as additional deep-sky objects. In place of the old barbell-shaped-projector, this one's main module is a black globe using fiber optics to produce some star images finer than the unaided eye's ability to resolve them.

But what makes the new Hayden a technological leap forward is its combination of analog and digital technology. While the analog Zeiss system is hardwired to portray specific celestial bodies, the digital projection system displays images and scientific visualizations created by computer. These systems can work together, for instance superimposing a digitally created comet trail against a Zeiss-projected sky. The Digital Dome System here is powered by a Silicon Graphics Onyx2 Infinite Reality workstation, which feeds output to seven projectors. This technology, originally developed for flight simulators in defense applications, creates in the Hayden three-dimensional tours of outer space. Its visual database of billions of stars was compiled by the American Museum of Natural History, with support from the National Aeronautics and Space Administration. Among Hayden II's advances is technology to remove the blurry edges between the projectors' overlapping image—a distraction in previous systems.

The analog and digital projection systems cost about $4 million each, and the Hayden's inaugural show—"Passport to the Universe"—makes extensive use of both. "We wanted to see what we could do once we had all the toys," explains James Sweitzer, the planetarium's director of special projects. The show also debuts a scientific triumph: the 3-D mapping of the Orion nebula from Hubble telescope data, allowing a spectacular *Star Wars*-like fly-through of that distant star grouping. What the digital system gains in flexibility and extensibility, however, it loses in definition; while it makes possible the highest-resolution virtual-reality theater open to the public, its stars pale beside the crispness of the Zeiss optically projected images.

There is a downside to this new technology. Where once the Hayden Planetarium's sky show lasted close to an hour and included informative discussions of constellations and star names, "Passport to the Universe" zips by in a mere 18 minutes. It gives only the briefest glimpse of the constellations. The compressed show enables the planetarium to give twice as many shows per day, compensating for the 200 fewer seats and massive construction costs. An adult ticket price of $19 (including admission to the Natural History museum) puts the outing in the same league as a top ride at Disneyworld (though the lines aren't as bad). Still, this 21st-century planetarium succeeds at what its predecessors have always done best: exposing visitors to the universe's grand scale of space and time, and filling us with awe. **—Steve Ditlea**

NET NUGGETS

Hooking Up: Bewildered by all those competing options for telephone, wireless, TV and Internet service? Come here for a nifty comparison engine. Type in your zip code and the amount you're willing to pay per month, and a comprehensive list appears. This venture-funded startup is offering the data now for New York, Boston and San Francisco, with plans to cover more of the country in coming months. www.getconnected.com

Net Numerology: Slice and dice online demographics in myriad ways with this fascinating collection of data—from what kind of browsers people are using to what search engines they rely on to what country they're logging in from—and, of course, how much money they're spending online. This site is a major crossroads, providing pathways to all the major number crunchers. Was ever a frontier settled under such a microscope? www.internetstats.com

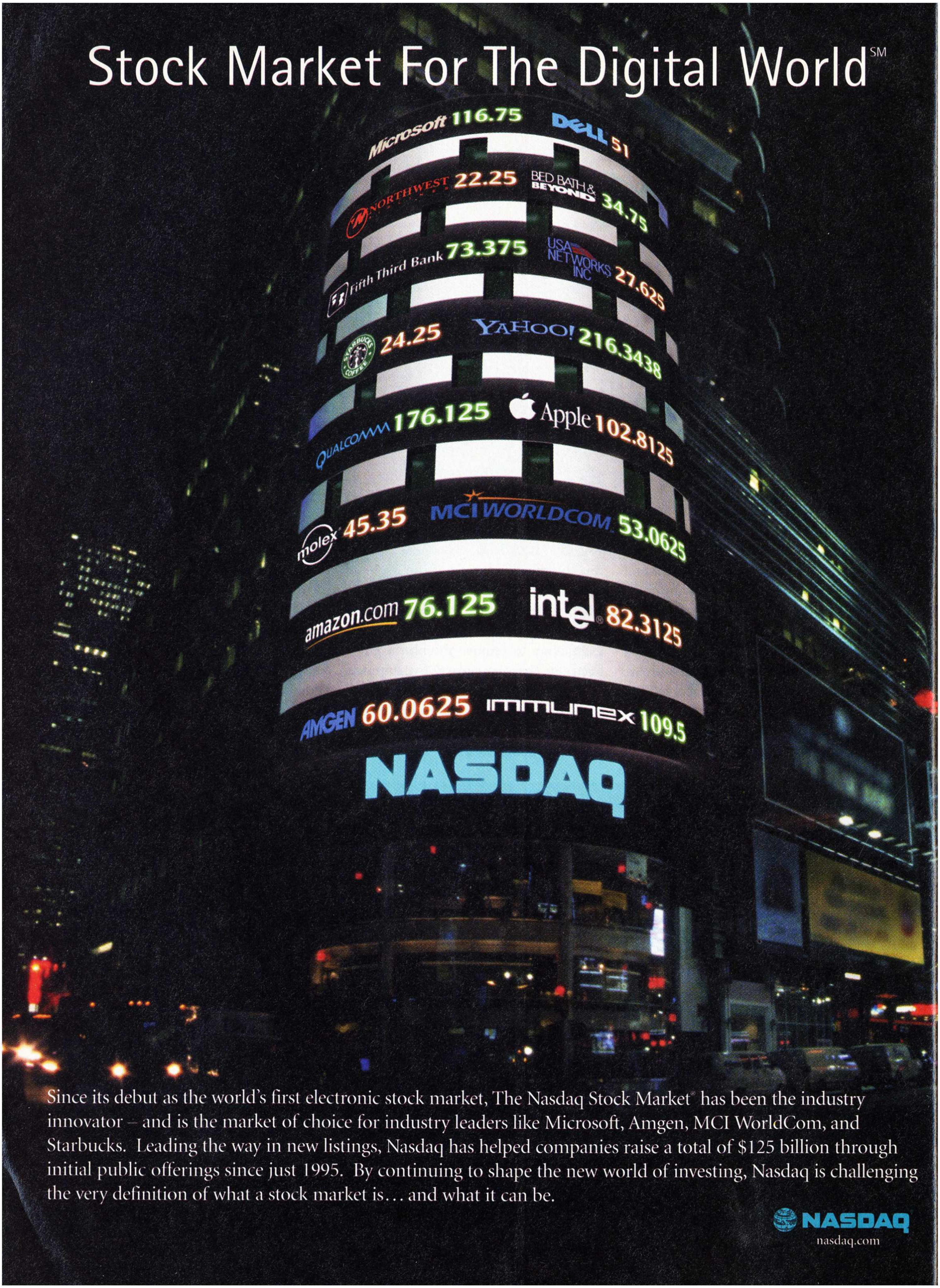
Southern Fried Internet: "Howdy, y'all, and greetings once again from sunny Tuscaloosa, Alabama!" Don't let the down-home greeting fool you—Internet Tour Bus is a fine and funny source of online intelligence. Its creators—writers Bob Rankin and Patrick Crispen—serve up authoritative tidbits about Web design, business and culture in an irreverent and folksy patter. Don't miss their "southern word home page."
www.tourbus.com

venues. A scaled-down *Unknown Anthology* book was scheduled, at press time, to be offered in May through Web sites XLibris and Fatbrain.

Sampling the novel on the Web is worthwhile. But the real novelty comes at a live reading. The different authors rotate through three roles: One reads, one works the mouse, and one dings a bell to alert the audience to each hypertext link. Audience members interact by calling out when they want to click on a link. When that happens, the authors break away from the page they are currently reading. An *Unknown* reading makes for a uniquely personal encounter with a medium that is usually about alienation.

The Unknown moves wittily between a megalomaniac register and self-deprecating banter. It riffs on literary styles, lampoons intellectual icons and even insults the reader for reading all the way through a long page. It comments on the nature of hypertext—and makes fun of itself for doing that. (One of the colored navigational paths is called "Metafictional Bullshit.") Amid the wackiness is some interesting story, which writer Robert Coover has praised as "massively rich."

"In some ways it's reacting against closure, the organizing principle of most books," says Rettberg. This reaction is a staple of hypertext fiction, taken up by the first hypertext novel, Michael Joyce's *Afternoon*. But in *The Unknown*, it's not just the many paths that keep the work from seeming "closed." The hypertext is also unfinished. The authors continue to add additional text about every other month. More readings are planned as well: Check for details at www.soa.uc.edu/user/unknown/greenline.htm. **—Nick Montfort**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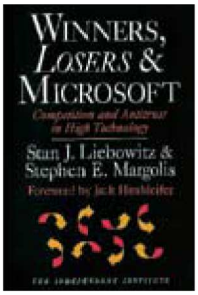
PAGES | BY WADE ROUSH

Benevolent Microsoft?

WINNERS, LOSERS AND MICROSOFT: COMPETITION AND ANTITRUST IN HIGH TECHNOLOGY
By Stan J. Liebowitz and Stephen E. Margolis
The Independent Institute, 287 pp., $29.95

Once one dismisses
The rest of all possible worlds
One finds that this is
The best of all possible worlds



SO LYRICIST JOHN LA TOUCHE paraphrased Dr. Pangloss in Leonard Bernstein's 1956 adaptation of *Candide*. What was true in Voltaire's day was true in Eisenhower's and in ours: Optimism can be taken too far.

The basic argument of *Winners, Losers and Microsoft,* a controversial study from Oakland, Calif.-based economic policy think tank The Independent Institute, is that we should all be happy that Microsoft dominates the market for PC operating systems, word processing, Web browsers and other software. Indeed, economists Stan Liebowitz and Stephen Margolis reveal, Microsoft products are so superior, and so useful when networked together, that we have collectively decided to give the company a virtual monopoly.

I have been unkind to Microsoft in these pages, but anyone who spends 10 hours a day using Microsoft products will understand my resentment. I would prefer an iMac to my PC, but everyone in my office uses a PC. I would prefer to run the Linux operating system on my desktop, but the office network depends on Windows. In short, I—and a great many others—have been locked into Microsoft technology not by choosing the best product but by network effects.

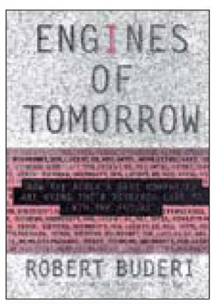
Lawyers at the Department of Justice see the same pattern; lock-in is one of the harms cited in their antitrust case against Microsoft. Liebowitz and Margolis, however, assert that in a free market, lock-in is impossible. The pattern they see is one of benign "serial monopoly" in which the firm with the best product dominates for a time, but is eventually and inevitably displaced by one with a better product.

For their key evidence against lock-in, Liebowitz and Margolis attempt to debunk examples frequently cited by technology journalists. The VHS and Beta video formats are, they argue, of comparable quality—VHS won out in the late 1970s because consumers preferred the longer recording times of the larger cassettes. While they're at it, they also argue that the original Macintosh OS was no better than DOS, that FORTRAN persists because it is economical and that the metric system offers no worthwhile advantages over the English system of measures.

Maybe Liebowitz and Margolis are right and maybe, as they complain, we journalists are simply "quick to file the bad-news stories of how the world is not only unfair, but also illogical." But that still doesn't get Microsoft off the hook, since the question in the antitrust case is whether the company bullied other firms in an illegal attempt to quell competition. And it doesn't explain why so many of us still feel locked in. If this is the best of all possible worlds, my name is Bill Gates.

Revved-Up

ENGINES OF TOMORROW: HOW THE WORLD'S BEST COMPANIES ARE USING THEIR RESEARCH LABS TO WIN THE FUTURE
By Robert Buderi
Simon & Schuster, 432 pp., $27.50



IN 1990, THE PREVAILING sense among technology watchers was that U.S. industrial research was in trouble, and that somebody had better do something about it quick. Nervous about Japanese competition in critical areas, democrats led a move to allocate $100 million for the Advanced Technology Program, 10 times more than President Bush had requested for the next fiscal year. Rejecting the administration's largely hands-off industrial policy, the House passed the measure by more than 3 to 1.

How things change. In computers, communications, biotech and other key technology areas, America has surged to the front of the pack while Japanese industrial growth has stagnated. The real credit for the turnaround goes to the big companies such as General Electric, AT&T and Hewlett-Packard that downsized and restructured their research labs in the early 1990s, shifting resources formerly squandered on basic research toward meeting the technology needs of real-world customers. That's according to Robert Buderi, a former editor at *Business Week* and a *TR* contributing writer, in his new book *Engines of Tomorrow*.

What Buderi heard in hundreds of interviews at dozens of companies was that their research labs had lost relevance and accountability, pumping out scientific papers and even Nobel Prizes—but contributing little to the corporate bottom line. Sometime between Sputnik and the breakup of the Soviet Union, industry leaders had developed an unquestioning faith in the power of basic science to drive technological innovation. As Buderi shows in two excellent chapters on the history of industrial research, this faith was partly justified; it took only a handful of brilliant chemists and physicists to give birth to the German chemical and pharmaceutical powerhouses in the 1880s, for example. But this kind of research had been results-driven. During the Cold War, by contrast, the government and corporate spending lavished on research freed many scientists to ignore product development.

Buderi's remaining chapters detail how IBM, Siemens, Bell Labs, GE and other industrial giants recognized and rectified this problem. Arno Penzias, the Bell Labs researcher who co-discovered the cosmic background radiation in 1965, exemplifies the change in thinking. As research vice president for the labs in 1989, Penzias realized that "the business units were going to need help, and we were going to have to do something about it." He pushed through a reor-

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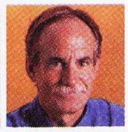
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ganization that refocused the lab on a few key areas, such as lasers and silicon, and put researchers in closer touch with product developers. The reorganization ultimately led to the formation of Lucent, one of the bull market's highest-flying technology companies.

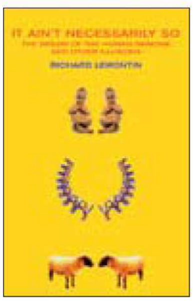
Buderi's narrative is flowing and lucid, and contains just enough detail to satisfy historians without overwhelming lay readers. My only criticism is that Buderi's writing sometimes falls into the mixed metaphors endemic in the business world. At Bell Labs, he writes, "The dam only broke when a steel-nerved manager went against the grain." But this is, as they say, a minor quibble. On the dog-eat-dog battlefield of business journalism, *Engines of Tomorrow* will get a lot of mileage.

Genome, Schmenome

IT AIN'T NECESSARILY SO: THE DREAM OF THE HUMAN GENOME AND OTHER ILLUSIONS

By Richard Lewontin

New York Review of Books, 330 pp., $24.95



IF RICHARD LEWONTIN IS RIGHT, we're in for a big letdown when the Human Genome Project is completed. The promise used to justify the $3 billion effort is that the 3 billion base pairs in human DNA make up a "Book of Life" that will reveal the secrets of development, disease and everything in between. But as Lewontin points out in *It Ain't Necessarily So*—a collection of nine extended pieces from *The New York Review of Books*—there are a few troublesome details scientists "forgot" to mention when they were lobbying for the project more than a decade ago.

For one thing, we have only the foggiest picture of how our 100,000 genes interact to regulate one another's expression and to direct protein production. Extrapolating from the genome to the whole organism is therefore akin to writing a history of New York City based on the phone directory. Another problem is that DNA, by itself, doesn't produce or explain anything. Genes specify which amino acids should be used to build a protein, but proteins themselves "are made by other proteins, and without that protein-forming machinery *nothing* can be made," Lewontin observes. Life, in other words, is a co-production between DNA and its cellular surroundings, the choreography of which cannot be recorded solely in the genome.

Lewontin, a renowned geneticist and evolutionary biologist at Harvard, blames the Genome Project's "fetishization" of DNA partly on the "evangelical enthusiasm" of prominent academic biologists with large personal financial stakes in the genomics industry, and partly on the gullibility of their journalistic "acolytes." But he also sees it as a continuation of biology's attempt since World War II to explain life in the same exact, mechanistic terms employed with such success by physicists earlier in the century. The problem is that where physics is neat and deterministic—"If you have seen one electron, you have seen them all," as Steven Weinberg puts it—biology is messy and multithreaded.

Lewontin's skillfully crafted reviews, which also cover books on evolution, embryology, sex research and cloning, say less about the books themselves than about Lewontin's sharp-witted skepticism and humility about nature's mysteries. "The truth is sometimes unavailable," he cautions—something biology's evangelists would do well to acknowledge.

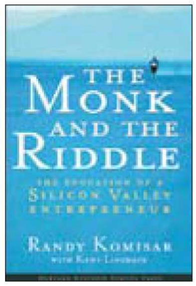
New Biz Classic

THE MONK AND THE RIDDLE: THE EDUCATION OF A SILICON VALLEY ENTREPRENEUR

By Randy Komisar, with Kent Lineback

Harvard Business School Press, 192 pp., $22.50

I'M GOING TO GO OUT ON A LIMB AND predict that *The Monk and the Riddle* will become the best-selling business book of the year. It will end up on the bookshelves of anyone who has considered leaving a comfortable job to start or join a startup. It could even become one of those slender classics, like *Silent Spring* and *Small Is Beautiful*, whose moral impact is in reverse proportion to its length.



Randy Komisar's business card reads "Virtual CEO," but he describes himself more as a consigliere to the inventors and entrepreneurs of Silicon Valley. An attorney who worked at Apple in its glory days, then led companies such as Claris, Go and LucasArts, Komisar now spends his afternoons advising startup executives. He spends his mornings in a Portola Valley café, listening to pitches from eager MBAs with the latest schemes for e-commerce. His instincts often determine whether the candidates fly or flop with the venture capital firms on Sand Hill Road in nearby Palo Alto.

Apparently, a morning came when Komisar had heard one too many proposals for a soulless, better-faster-cheaper e-tailing site. "Lenny," his fictional amalgamation of go-getters, comes to Komisar with a proposal to start "Funerals.com," intended to undercut local mortuaries by selling cheap caskets online. Komisar tries to explain to Lenny that VCs aren't likely to fund him unless he seems truly passionate about the idea. Komisar calls Lenny's strategy the "Deferred Life Plan"—do something dull and predictable now, promising yourself you'll follow your passion later. It's only when Lenny's partner reveals their original vision—an online community for grieving families—that Komisar sees a spark. Lenny hadn't put this into his plan because he couldn't see how to profit from it. But far worse than failing to make money, Komisar argues, would be failing to follow one's dreams.

It may sound sappy, but Komisar bolsters his message by relating how he learned the lesson himself, beginning with his decision to join Apple. "When I considered the risk of staying at my law firm, I had to face the possibility of an unfulfilled life, of working endlessly on things that did not matter," Komisar writes. "To me these were graver risks than whether Apple succeeded or failed." Fictional Lenny eventually grasps Komisar's point: the Deferred Life Plan is more expensive than it looks. If they can tear themselves away from their stock options and IPOs for a moment and read *The Monk and the Riddle*, a lot of real Silicon Valley entrepreneurs might learn the same thing. ◊

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MIT MUSEUM

Computing Before Silicon

The differential analyzer showed the world machines could compute

HISTORIANS DISAGREE ABOUT HOW TO CATEGORIZE THE machine pictured above. Was it the first computer? A mammoth mechanical calculator? But there is no question that the differential analyzer—shown with its inventor, MIT's Vannevar Bush—was a crucial player in the history of computing.

Bush designed the device to solve differential equations in an attempt to model the rapidly expanding power systems of the 1920s. When completed in 1931, the analyzer used electric motors to drive shafts and gears that represented each term in a complicated equation.

The differential analyzer showed the world that machines were suited not just for physical labor, but for mental labor as well. It alerted researchers and funders to the profound possibilities of computers. Bush became director of the Office of Scientific Research and Development—precursor to the National Science Foundation. But though his vision helped shape the government's attitude toward science, Bush had a blind spot when it came to the digital revolution: He refused to fund early projects in digital computing, including the University of Pennsylvania's landmark ENIAC. And though the differential analyzer was, in Bush's words, "the first of the great family of modern analytical machines to appear—the computers, in ordinary parlance," today's PCs aren't direct descendants of his contraption. Bush's was an analog machine; it represented numbers with physical qualities that vary continuously—distance, rotation and so forth—rather than with the discrete 1s and 0s of digital devices.

Still, the differential analyzer was a critical, if inadvertent, midwife to the birth of digital technology. While laboring over the machine and observing the logic of its action, one of Bush's students—a mathematician named Claude Shannon —began thinking of new ways to build circuits. Shannon realized that the "true" and "false" of Boolean algebra could be represented by the "on" and "off" positions of an electrical switch—in other words, he came up with the idea of a bit.

Shannon's work with the differential analyzer led to a thesis published in 1938 that has been called "one of the most important master's theses ever written." In it, Shannon laid out the logic upon which all digital circuits are now based. ◊

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This story was suggested by *TR* contributor M. Mitchell Waldrop, whose book on the history of computing is due out next spring.
Send a few paragraphs to: Trailing Edge, *Technology Review*, MIT Building W59-200, Cambridge, MA 02139; or e-mail: trailingedge@techreview.com.

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